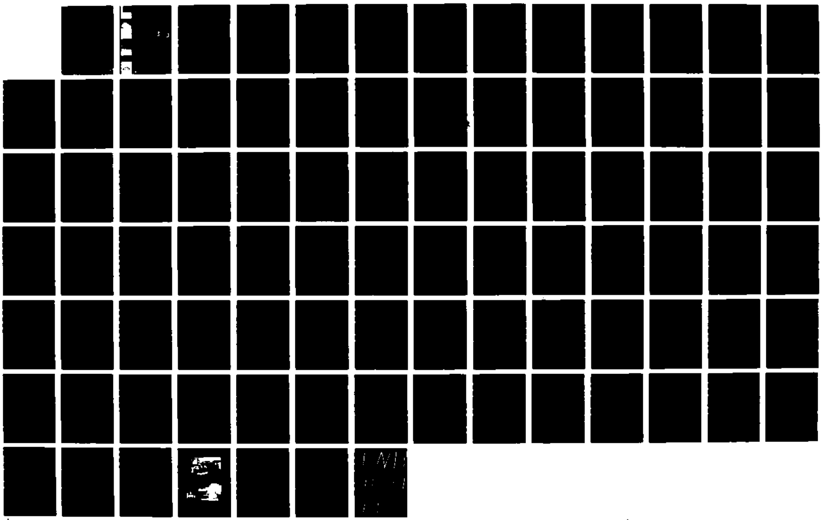
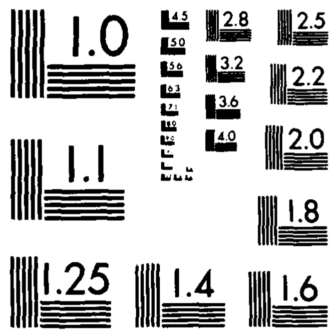
AD-A185 485 DRY-SOIL COMPACTION INVESTIGATION(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS GEOTECHNICAL LAB W N BRABSTON AUG 87 WES/TR/GL-87-19 1/1

UNCLASSIFIED F/G 8/10 NL

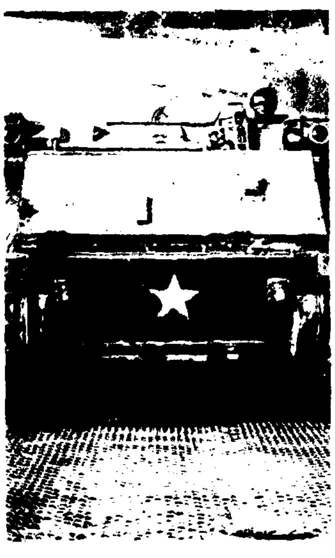



1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

(12)

TECHNICAL REPORT GL-87-19

US Army Corps of Engineers



DRY-SOIL COMPACTION INVESTIGATION

by

William N. Brabston

Geotechnical Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

August 1987

Final Report

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

and

Air Force Engineering and Services Center
Tyndall Air Force Base, Florida 32403

GEOTECHNICAL LABORATORY

043

A185 485

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) WES/TR Technical Report GL-87-19	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAEWES Geotechnical Laboratory 6b. OFFICE SYMBOL (If applicable) WESGP-R	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION US Army Corps of Engineers and Air Force Engineering and Services Center 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000 Tyndall Air Force Base, FL 32403	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO. F84-63 | TASK NO. | WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Dry-Soil Compaction Investigation

12. PERSONAL AUTHOR(S)
Brabston, William N.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM ______ TO ______	August 1987	88

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Compaction; Soil compaction; Dry compaction; Vibratory rollers; Impact rollers

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Objectives of this field study were to investigate means of compacting soils at near-zero water content. Two 125-ft-long test sections were constructed, each consisting of five test items 25 ft long with a 5-ft-deep test bed. In each test section, the first item consisted of 1.5 ft of crushed limestone (GW) over 3.5 ft of bomb-crater debris. The remaining four items consisted of 5 ft of silty clay (ML), river sand (CL-ML), gravelly sand (SP), and sand tailings (SP), respectively. One test section was compacted with a single drum self-propelled vibratory roller and the other with a towed four-sided impact roller.

Test results were not fully conclusive because of the difficulty in drying soils with fines, rotational slippage of the impact roller during testing, and precompaction of the

(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) | 22c. OFFICE SYMBOL

19. ABSTRACT (Continued).

cont'd

soils in the vibratory roller test section during construction. However, it could be concluded that (a) compaction at low water content was feasible primarily with soils with few fines, (b) significant difficulty would be experienced in field-drying soils with high fines content, (c) both compactors generally gave acceptable results, but the rate of compaction of the impact roller was much higher than that of the vibratory roller, and (d) test results warranted further investigation of compaction with the impact roller.

PREFACE

This investigation was sponsored by Headquarters, Office, Chief of Engineers (OCE), under Operation and Maintenance, Army (O&MA), funding and the Air Force Engineering and Services Center (AFESC) Project Order No. F84-63. The project was conducted under the OCE Facilities Investigation and Studies Program. The Technical Monitors for this investigation were Mr. A. Muller, DAEN-ECE-G, and Mr. Jim Green, DEMP.

The study was conducted by personnel of the Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), under the general direction of Dr. W. F. Marcuson III, Chief, GL; Mr. H. H. Ulery, Jr., Chief, and Dr. T. D. White, former Chief, Pavement Systems Division (PSD), GL, WES. Principal Investigator was Dr. W. N. Brabston. Other engineers and technicians actively engaged in the testing, analysis, and reporting phases of the study were Messrs. J. W. Hall, R. W. Grau, and T. P. Williams and Ms. M. D. Alexander. This report was prepared by Dr. Brabston and edited by Mrs. Joyce H. Walker, Information Products Division, Information Technology Laboratory.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
foot-pounds (force)	1.355818	metre-newtons or joules
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimetres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

DRY-SOIL COMPACTION INVESTIGATION

PART I: INTRODUCTION

Background

1. Field compaction of soils is generally envisioned as being undertaken with the soil at some nonzero optimum moisture content at which maximum density will be obtained. Circumstances, however, may dictate that field compaction be accomplished with the soil at a water content considerably drier than the conventional optimum value or even at- or near-zero water content. Such circumstances may include physical characteristics of the particular soil involved, prevailing soil-moisture conditions in the construction environment, or other physical constraints such as scarcity of water.

2. It is well recognized that the optimum moisture content of a soil is determined from the moisture-density relations of that soil, as indicated by a standard laboratory compaction test. For fine-grained soils, the optimum moisture content generally occurs at some nonzero value associated with the maximum or peak dry density, as shown on the moisture content-dry density plot (Curve A, Figure 1). For sands and some other coarse-grained materials, the characteristic curve may indicate two peak values -- one at zero water content and one at a nonzero value (Curve B, Figure 1). For such a material, it is considered accepted practice for field compaction to be conducted at either water content. For some coarse-grained materials, the relationship may be essentially linear with no definable peak (Curve C, Figure 1). For a material of this type, it is obvious that field compaction should be conducted at as high a water content as feasible and, conversely, compaction at a low water content would not yield an acceptable density. In addition to these familiar shapes, irregularly shaped compaction curves have also been demonstrated which have several peaks of high density at several different water contents (Curve D, Figure 1) (Lee and Suedkamp 1972).

3. Environmental constraints may also dictate soil-water content conditions. In developing countries, particularly those in the arid regions of the world, sources of water may be scarce or unavailable. Military operations

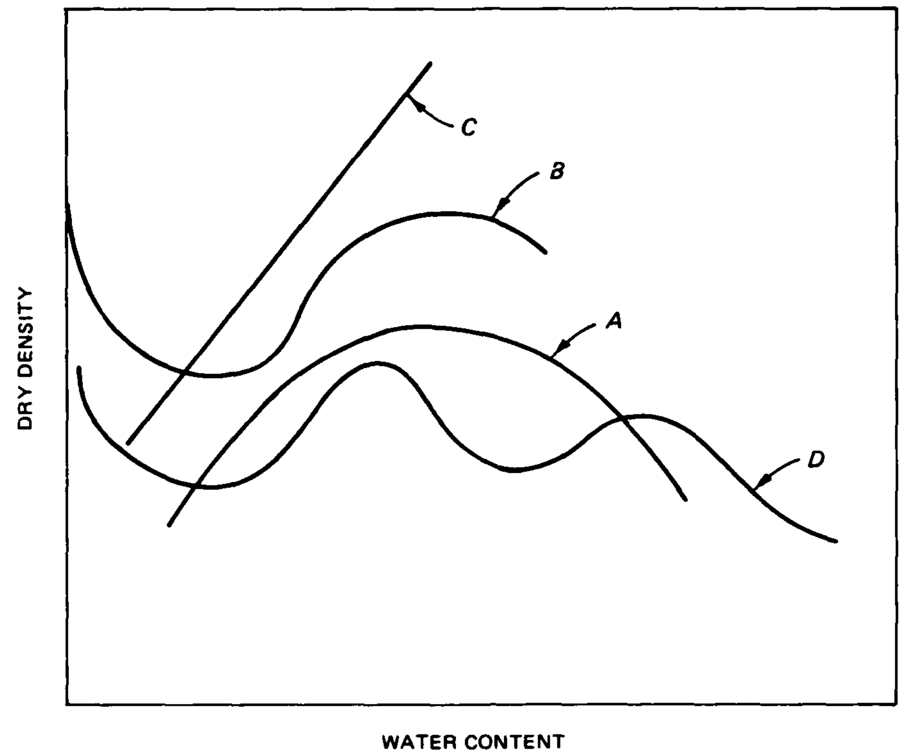


Figure 1. Idealized moisture-density curves

that involve rapid movement can also preclude development of adequate water sources because of time constraints.

4. Experience indicates that most fine-grained soils are best compacted at a nonzero water content; however, dry-soil compaction is recognized as a feasible approach for some coarse-grained materials such as free draining sands and some rock materials in large fills.

5. The approach to dry compaction in the field generally involves the use of vibratory compaction equipment (such as drum rollers or plate vibrators) that input steady-state dynamic loadings to the soil so that the particles settle or collapse into a state of minimum energy or maximum density. A publication of Forssblad (1981) provides excellent guidance on the use of vibratory drum and plate rollers and contains specific information on dry-soil compaction.

6. In addition to drum and plate compactors, another concept that has been developed for dry-soil compaction is the use of towed impact rollers. Towed impact rollers incorporate the feature of a drum having flat sides or faces, usually four to six in number, each of which strikes the soil as the drum pivots about the corner or intersection of two faces, thus imparting an

impact force to the material being compacted. Based on recent favorable reports (Clifford 1982; Ridgen and Clifford 1981), a towed impact roller having a four-sided drum was included in this study for evaluation of performance on several types of soils.

Objectives

7. The overall objective of this study was to investigate compaction of soils at near-zero water content with emphasis on materials typical of arid regions. Specific objectives were to evaluate the performance of a vibratory self-propelled drum roller and a towed impact roller in compaction of different types of soils and granular materials.

Scope

8. Two test sections were constructed, each consisting of five test items composed of five different soil types. Compaction tests were conducted in one test section with a vibratory drum roller and in the second test section with the towed impact roller. Parameters used in evaluating roller effectiveness were (a) visual observations during roller operations, (b) surface deformation, and (c) changes in soil density. Dynamic cone penetrometer (DCP) data were also obtained; however, they could not be statistically correlated with soil density or strength.

PART II: COMPACTION EQUIPMENT, TEST SECTIONS, AND FIELD TESTS

Compaction Equipment

Vibratory compactor

9. The vibratory compactor used in this study was a self-propelled compactor equipped with pneumatic drive wheels and a single vibratory drum having a length of 84 in.* and a diameter of 60 in. (Photo 1). Operating weight of the roller was about 23,000 lb. Static drum weight was 12,566 lb. During compaction, the roller was operated at a drum frequency of about 40 Hz which developed a drum centrifugal force at approximately 36,000 lb. Operating speed was approximately 328 ft/min.

Impact compactor

10. The impact roller is a towed compactor having a single four-sided drum suspended in a wheeled frame (Photo 2). The drum is approximately 4.27 ft long and spacing between sides is approximately 4.92 ft. Drum weight is about 15,900 lb. The compactor was towed by a 1,000-hp pneumatic-tired commercial tractor at a speed of approximately 700 ft/min. During operation, the wheels were raised so that only the rotating drum was in contact with the soil, thus delivering low-frequency high-amplitude compaction blows. A spring damping system subdued the horizontal jerking motion of the compactor allowing a relatively smooth pull during towed operations.

Test Sections

Description of soils

11. Six types of soil and gravel materials were used in the test program -- crushed limestone (GW),** an unclassified debris material consisting of silty soil, sand, gravel, and concrete fragments, all from a simulated airfield bomb crater; a silty clay (ML),** derived from local loess deposits; a blended material commercially termed river sand (CL-ML);** a gravelly sand (SP);** and sand tailings from a wash gravel processing plant (SP).**

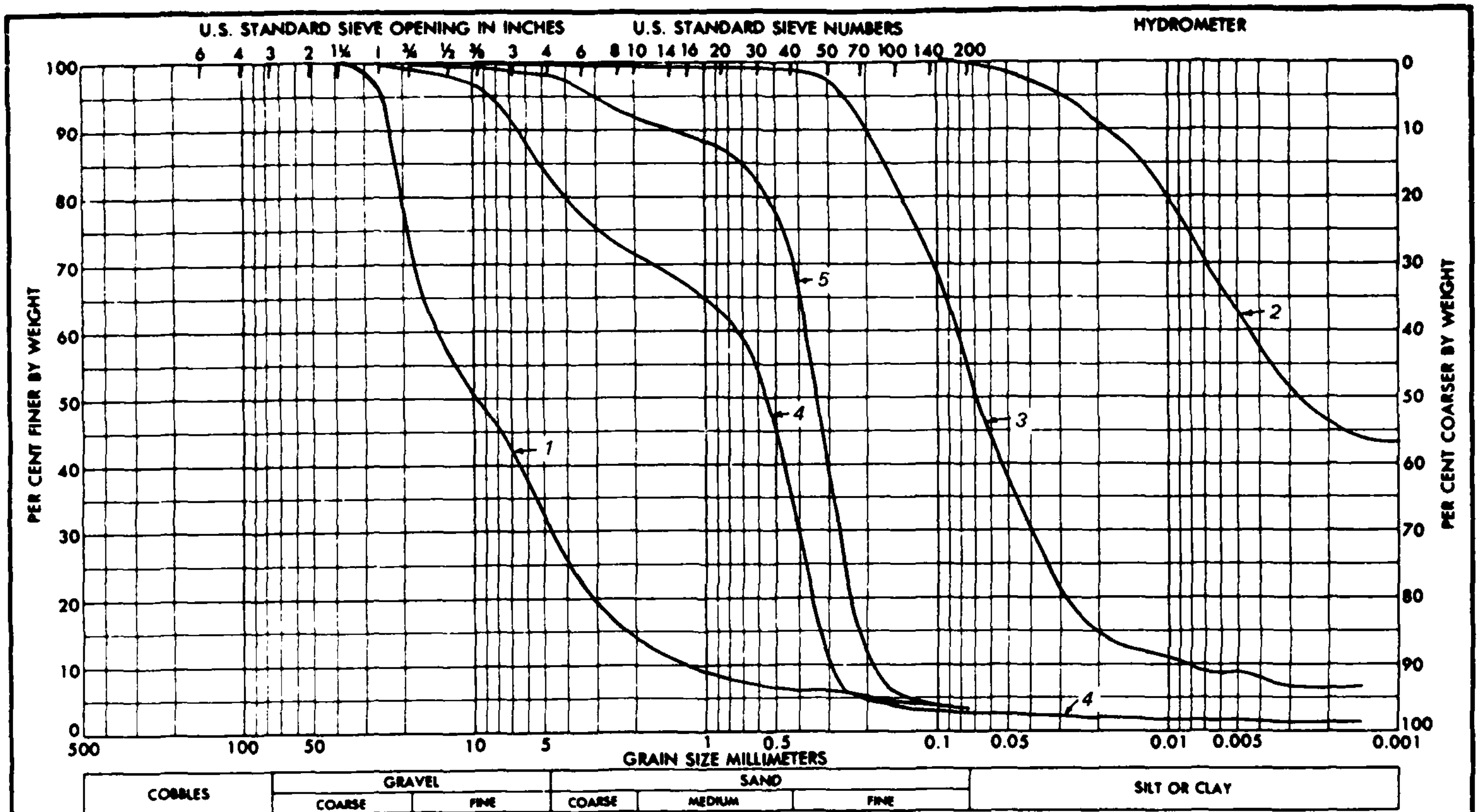
---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

** Classified according to the Unified Soil Classification System or ASTM D-2487.

Gradation curves and Atterberg limits for all soils except the debris material are shown in Figure 2. Because of the random nature of the debris material, no laboratory tests were conducted on the soil. From these curves, it may be seen that the limestone, gravelly sand, and sand tailings were all nonplastic materials and the silty clay and river sand were of low plasticity. The plasticity indices for the silty clay and river sand were 4 and 5, respectively. The crushed limestone had a maximum particle size of about 1-1/2 in. with about 3 percent fines (i.e., particle size smaller than 0.074 μm) and classified as a well-graded gravel. The gravelly sand and sand tailings are both predominately sand materials and classify as poorly graded sands. Both also have a fines content of about 3 to 4 percent. The material termed river sand was actually a blended material, and, although the gradation curve indicates a fines content of 55 percent, which classifies the soil as fine grained, tests on several pit samples indicate that the fines content may vary from 45 to 55 percent. Thus, the soil may be viewed as borderline sand-silt. The lean clay soil is a fine-grained material with practically 100 percent fines.

12. Moisture-density curves for the five classified soils are shown in Figures 3-7. For each soil, three compaction curves were developed representing three different compaction energy levels -- CE-12-, 26-, and 55-compaction efforts, as defined in Military Standard (MIL-STD) 621 (Department of Defense, in preparation). The numbers refer to the compaction energy in thousands of foot-pounds of energy per cubic foot of soil. The CE-12 and CE-55 methods are comparable with the ASTM D-698 and D-1557 test methods, respectively, while the CE-26 method involves an intermediate compaction effort of approximately 26,000 ft-lb/cu ft. From Figure 3, it may be seen that the compaction curves for the crushed limestone are characteristic of a granular material with low fines content and indicate that highest density may be achieved at either near-zero water content or a water content of about 7 to 9 percent. Near-zero water content, the maximum dry density for the CE-55 compaction effort, was 132.5 lb/cu ft. Compaction curves for the silty clay (Figure 4) are generally representative of a typical fine-grained soil. The maximum dry density for the CE-55 effort was 115.5 lb/cu ft at 14.8 percent water content. The river sand was technically a fine-grained soil although tests on several samples indicated that the fines content varied from 45 to 55 percent. However, compaction curves for this material (Figure 5) displayed characteristics of a



SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
1		CRUSHED LIMESTONE (GW)				NP
2		SILTY CLAY (ML)		28	24	4
3		RIVER SAND (CL-ML)		20	15	5
4		GRAVELLY SAND (SP)				NP
5		SAND (SP)				NP

PROJECT

AREA

BORING NO

DATE

GRADATION CURVES

ENG FORM 2087 1 MAY 63 REPLACES WES FORM NO 1241, SEP 1962, WHICH IS OBSOLETE.

U S GOVERNMENT PRINTING OFFICE 1963 OF—790-126

Figure 2. Soil classification and gradation data

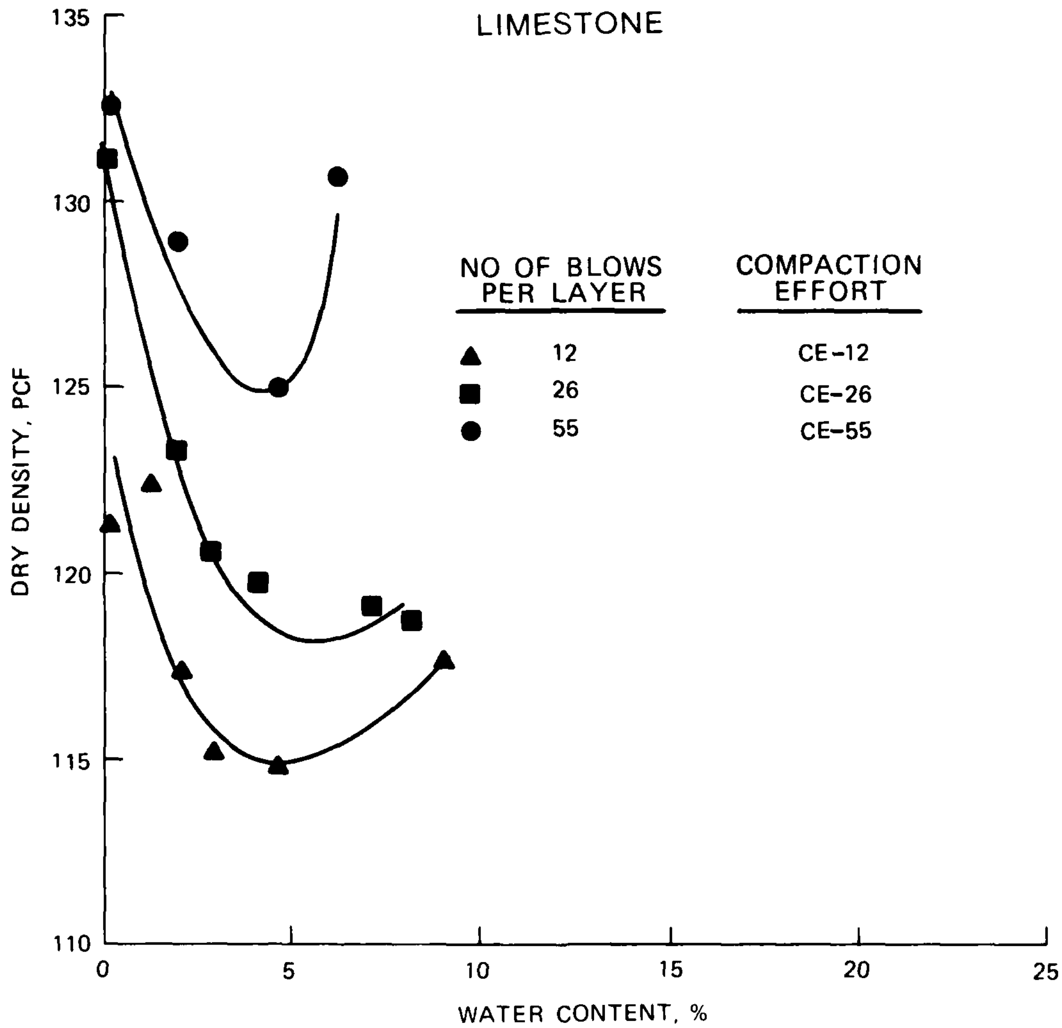


Figure 3. Moisture-density relations, crushed limestone

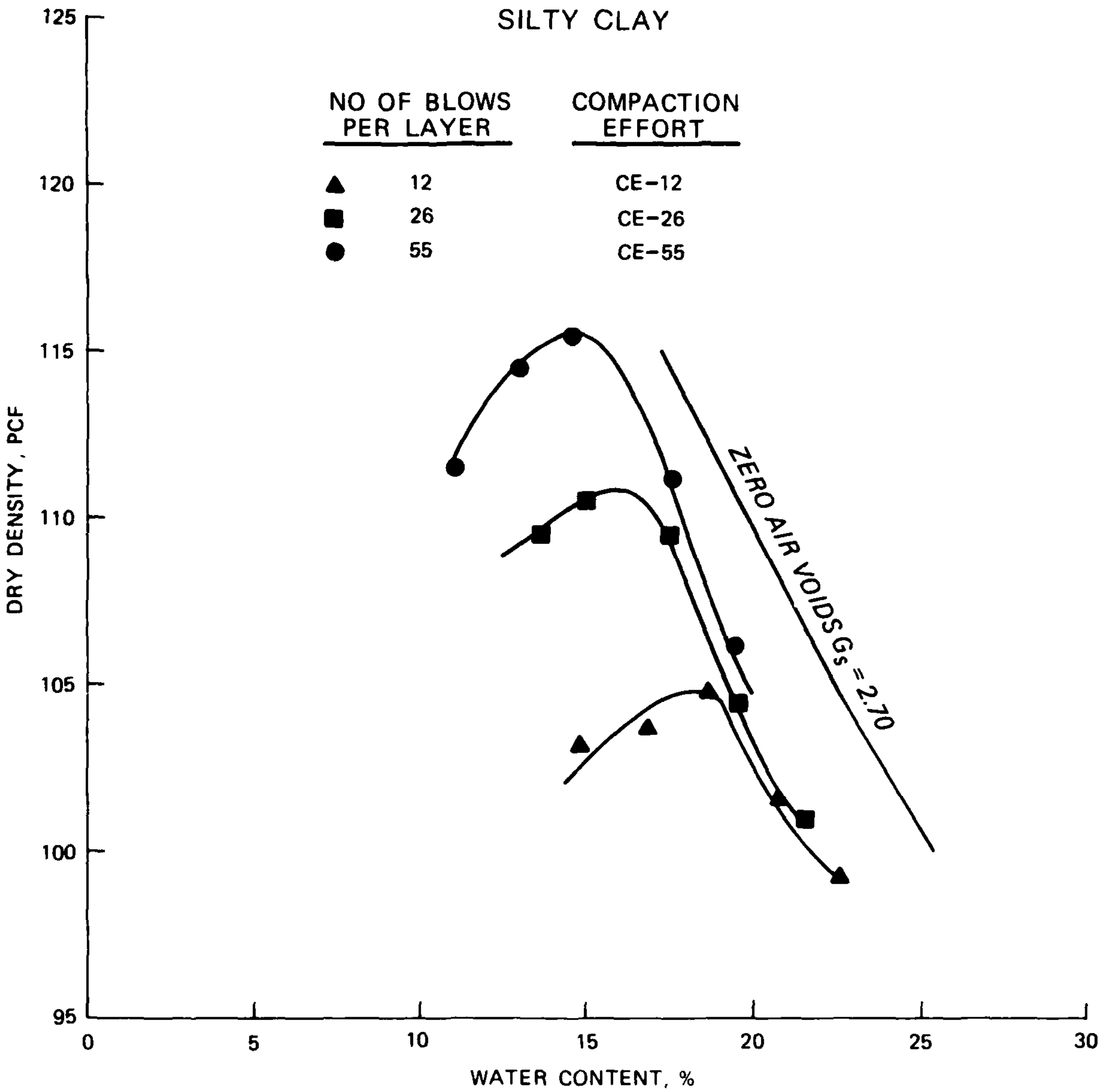


Figure 4. Moisture-density relations, silty clay

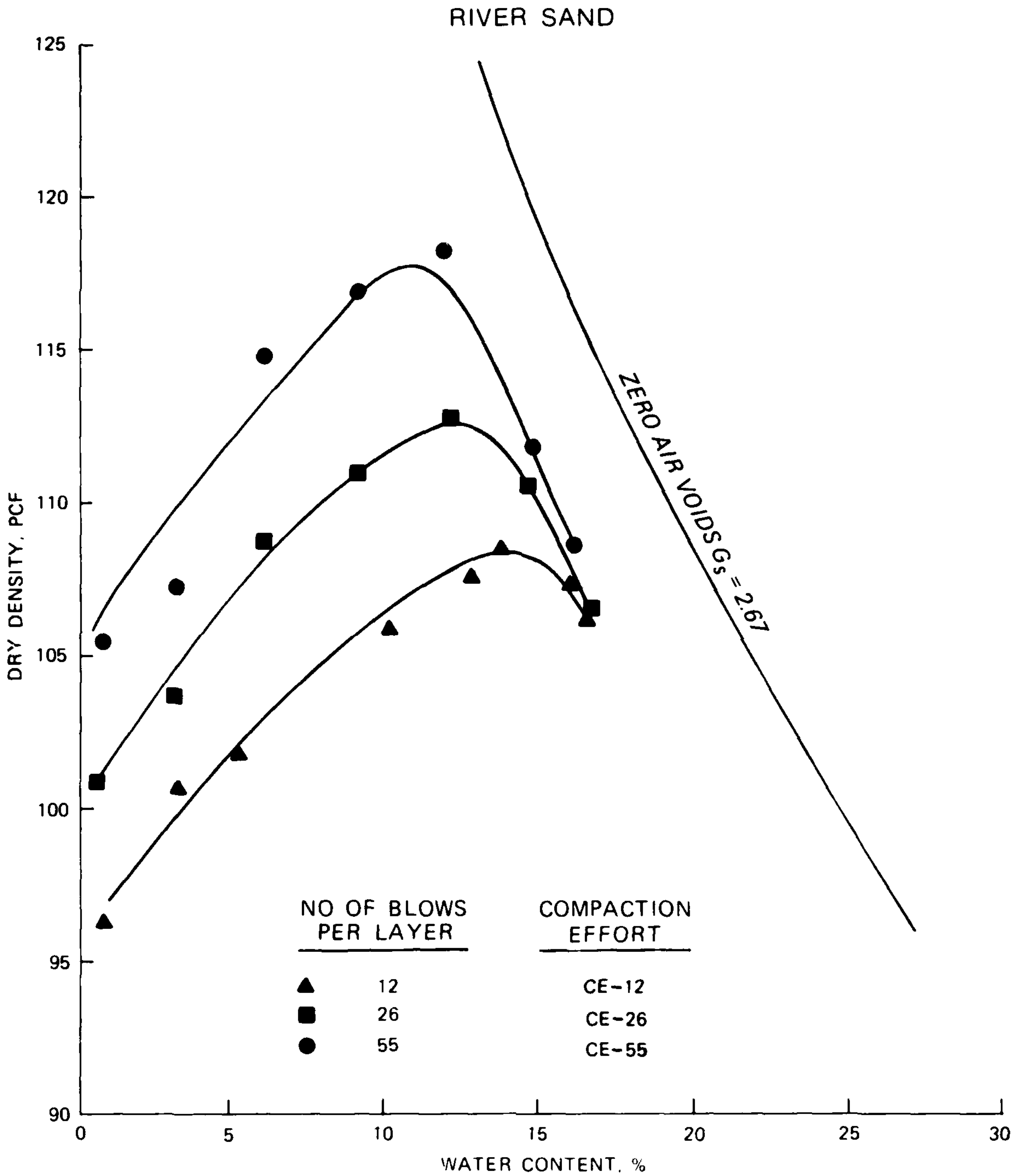


Figure 5. Moisture-density relations, river sand

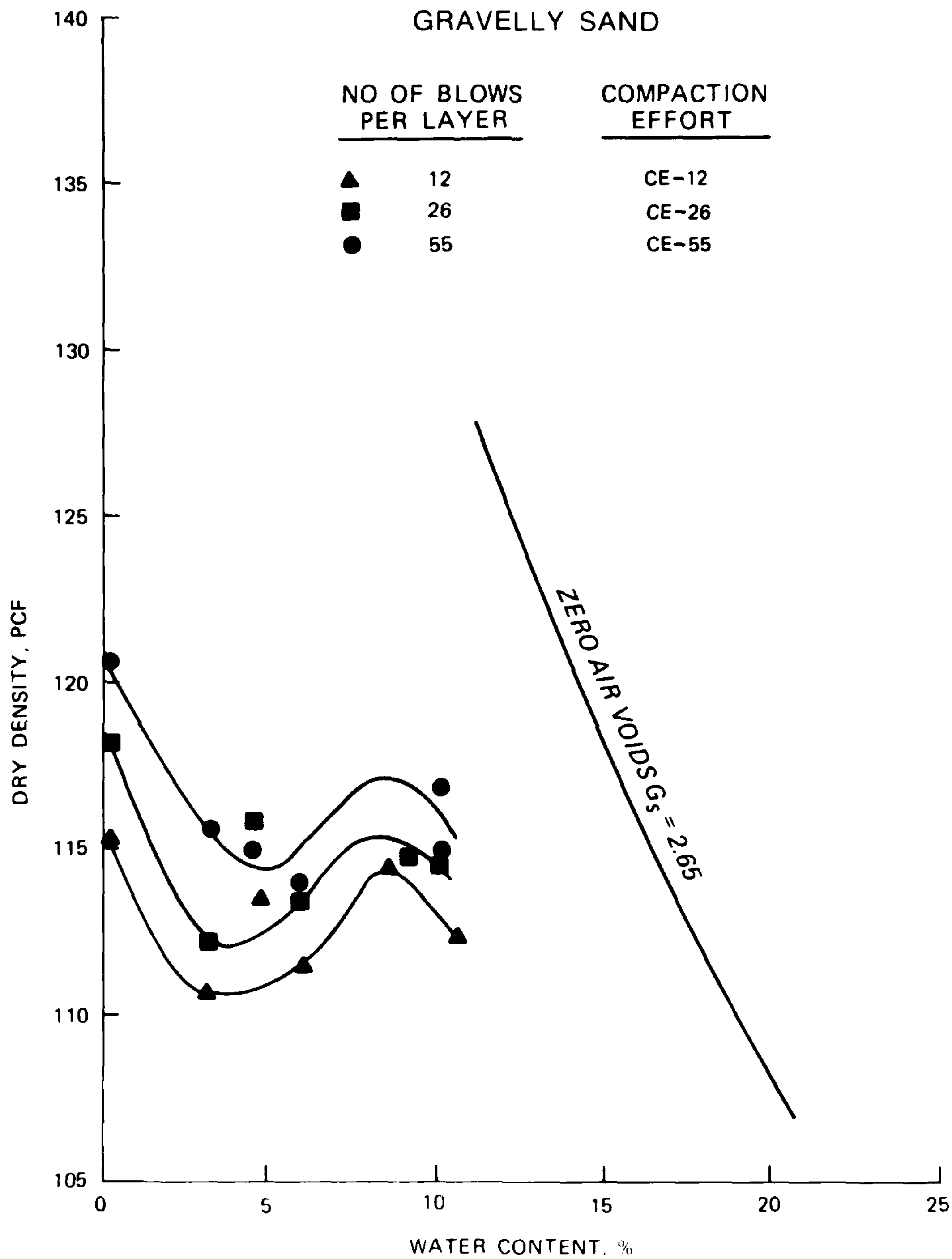


Figure 6. Moisture-density relations, gravelly sand

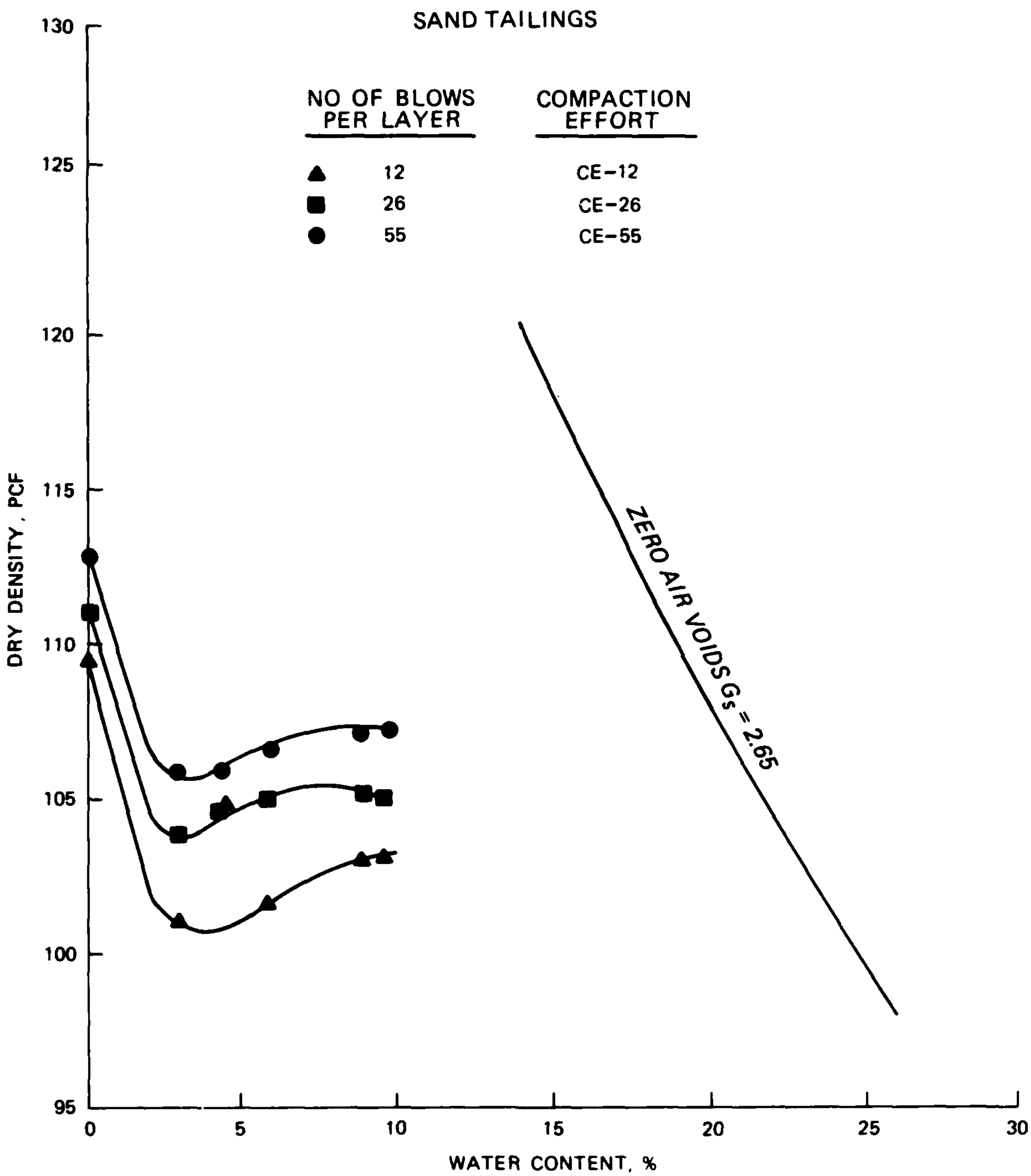


Figure 7. Moisture-density relations, sand tailings

fine-grained soil with a maximum CE-55 density of 117.7 lb/cu ft at an optimum water content of 11 percent. Compaction curves for the gravelly sand (Figure 6) were characteristic of a granular material. The maximum CE-55 density was 120.7 lb/cu ft at near-zero water content. Moisture-density curves for the sand tailings (Figure 7) were also representative of granular soils. For this material, the maximum CE-55 density at near-zero water content was 113.0 lb/cu ft.

Test Section No. 1

13. The vibratory compactor was used for compaction in Test Section No. 1. A plan and profile of the test section are shown in Figure 8. The test section was 125 ft long and 15 ft wide and consisted of five test items each 25 ft long and 15 ft wide. Depth of soil in each test item was 5 ft. The test section was located in a sheltered area for controlled conditions. Item 1 consisted of 1.5 ft of crushed limestone over 3.5 ft of debris material. Items 2, 3, 4, and 5 consisted of silty clay, river sand, gravelly sand, and sand tailings, respectively. Each item was constructed in eight individual lifts to a total thickness of 5 ft. The vibratory compactor was applied uniformly over the full width of the test section; however, only a 7-ft-wide strip down the center of the test section was designated for sampling purposes. This lane is referred to as lane 1.

Test Section No. 2

14. The impact roller was used for compaction in Test Section No. 2. A plan and profile of the test section are shown in Figure 9. The test section was 125 ft long and 26 ft wide and consisted of five test items each 25 ft long and 26 ft wide. Depth of soil in each item was 5 ft. The test section was also located in a sheltered area. Item 1 consisted of 1.5 ft of crushed limestone over 3.5 ft of debris material which was placed in one lift. Items 2, 3, 4, and 5 were constructed of silty clay, river sand, gravelly sand, and sand tailings, respectively. These latter four test items were constructed in two lifts, each approximately 2.5 ft thick. Three compaction lanes were delineated on the test section. Each lane was approximately 4.27 ft (1.3 m) wide, corresponding to the width of the compactor drum, with approximately 2.73-ft spacing between lanes. Spacing between lanes was provided primarily to minimize surface roughness in the path of the tractor wheels. Technical information for this compactor indicates that deep compaction in this zone is achieved as a result of projection of compaction energy horizontally or

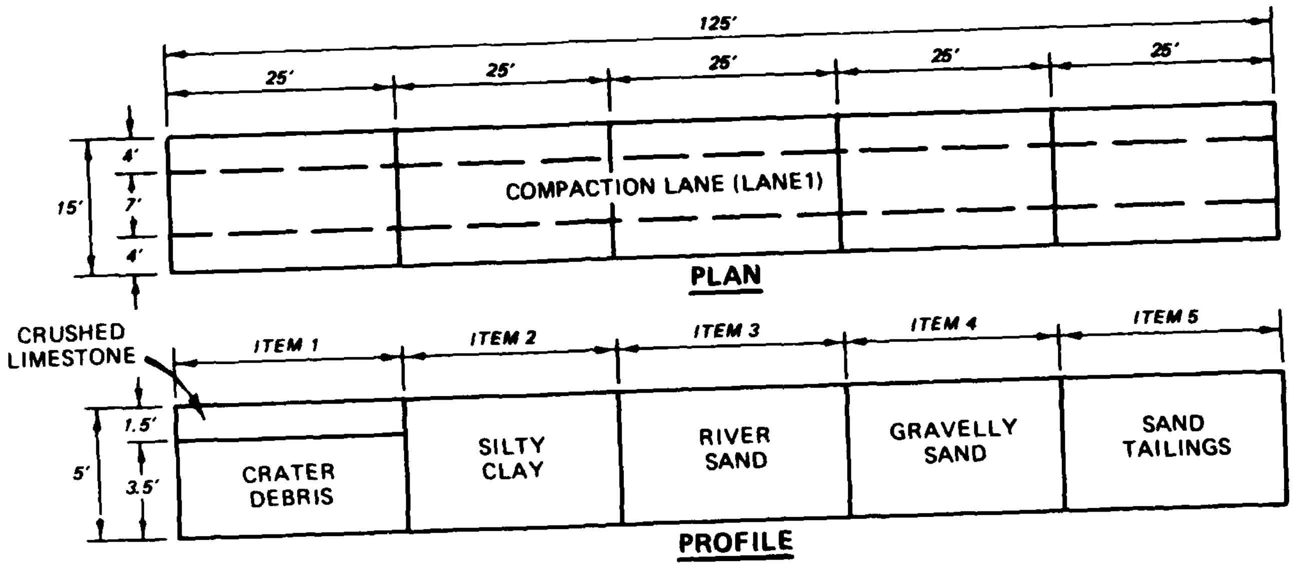


Figure 8. Plan and profile, Test Section No. 1, vibratory roller

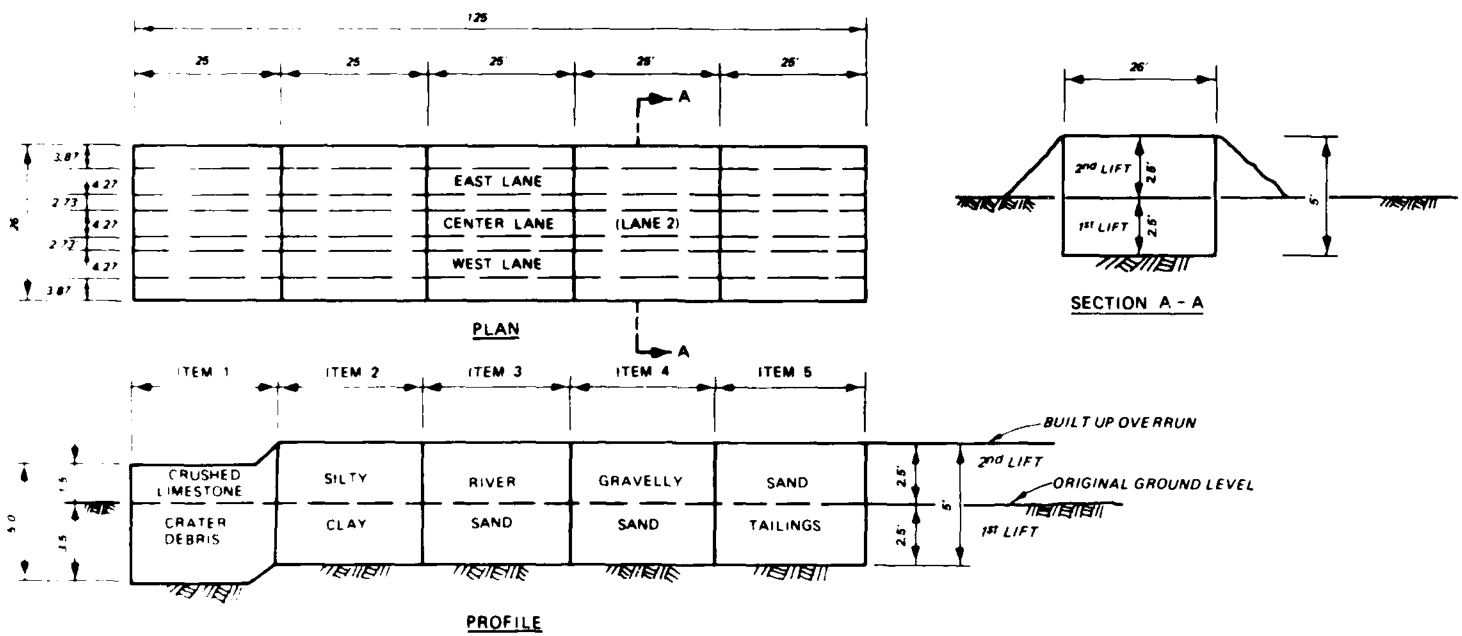


Figure 9. Plan and profile, Test Section No. 2 impact roller

vertically from compaction lanes on either side of this zone. This arrangement precluded trafficking of the tractor over the heavily corrugated and extremely rough surface that develops in the path of the compactor drum. Only the center lane was used for sampling purposes. This lane was designated as lane 2.

Field Tests

Processing of soils

15. Since the primary purpose of the study was to investigate means of compacting dry soils, it was desired that the granular materials be processed to as low a water content as practical prior to compaction. Because of the large quantities of soil involved, the only practical method of reducing water content was air drying in an open, exposed area. Therefore, on each day that drying conditions were favorable, the soil to be processed was spread to a depth of 6 to 10 in. on an asphalt concrete apron. Several times during the day, the soil was further aerated by means of a self-propelled rotary tiller. At the end of each daily drying period, the soil was covered with large sheets of waterproof membrane for protection against possible rainfall. This process was repeated until the soil-moisture content was reduced to an acceptable level or until it became apparent that expenditure of further processing effort was unproductive. It must be noted that scheduling constraints dictated that this phase of field operations be conducted during November and December, a period during which drying conditions are generally not optimal.

16. Following these procedures, the crushed limestone was processed to an average water content of about 2 percent prior to placement. No attempt was made to adjust the moisture content of the debris material which had an average in situ moisture content of about 9 percent.

17. The silty clay soil was a fine-grained material, and, after much effort to reduce the water content to near zero, it was decided that it would be more expedient to place the soil at a water content near optimum for the CE-55 maximum density. Therefore, the average placement water content for this material was approximately 15 to 16 percent. As indicated previously, although the river sand was technically a fine-grained soil, grain-size analysis on several samples indicated that the fines content may vary from 45 to 55 percent. Therefore, since the thrust of this study was on dry-soil

compaction with emphasis on desert-type soils, it was decided to attempt to dry this soil as much as possible. After considerable effort had been expended in field processing, the lowest practical water content that could be achieved was about 6 percent. Some difficulty was also experienced in drying the gravelly sand and sand tailings. The average placement water content of these materials was about 4 to 5 and 2 to 3 percent, respectively.

Test Section No. 1

18. Placement and compaction of soils. An excavation 125 ft long, 15 ft wide, and 5 ft deep was made at the test site. The soils were transported to the site and placed by dump truck and spread to the correct thickness with a small crawler tractor. Sufficient quantities of each soil were placed in the excavation at the appropriate location of each item to form a loose lift about 8 in. in thickness. After each lift had been placed, soil density and moisture-content data were obtained. Next, four passes of the vibratory roller were applied over the full width of the test section. A fixed number of passes was used for two reasons -- first, in accordance with the developer's recommendations, a fixed number of passes was to be applied with the impact roller; therefore, passes were not used as a variable in this study; second, experience with the vibratory roller has indicated that approximately four passes would be sufficient. This procedure was repeated for each lift. Eight lifts were required to complete the test section.

19. Field soil data. All field sampling and tests were conducted within the center 7-ft-wide test lane. Field data included in-place soil density and water content, surface elevations before and after compaction, and DCP readings. Density and water-content data were taken immediately prior to application of the vibratory roller on each lift and again after completion of the test section through test pits. Soil-density data were obtained in the limestone by the water balloon method and in the other soils by nuclear density meter (direct transmission method) with drive-cylinder correlations. All water contents were obtained by the oven-drying method. Postcompaction data were taken at 12-in.-depth increments. DCP data, which give an indication of the change in resistance of the soil to penetration, were obtained by driving the penetrometer into the soil with an 8-kg hammer and recording the depth of penetration. Penetration readings were obtained after each 10 blows of the hammer following the placement of soil lifts 1-4 in items 1-3, and after 5 blows following the placement of lifts 1-4 in items 4 and 5. After the placement of

all eight lifts in items 1-5, data were taken using 5-blow increments. Generally, it was attempted to develop penetration to a depth of 1,000 mm.

Test Section No. 2

20. Placement and compaction of soils. Since the actual test area required for the compaction tests was considerably narrower than that needed for maneuverability of the equipment, the basic width of the test bed was 26 ft. An excavation was thus made 26 ft wide and 125 ft long and of sufficient depth to receive the first lift only so that, after placement of this lift, the surface of the test section was flush with that of the surrounding unexcavated area. Thus, the area for item 1 was excavated to a depth of 3.5 ft and the area for the remaining items was excavated to a depth of 2.5 ft. The first lift of soil for each item was then placed in the respective location. In item 1, this consisted of 3.5 ft of unclassified debris and for items 2, 3, 4, and 5 of silty clay, river sand, gravelly sand, and sand tailings, respectively. The soils were transported from the processing site by truck, dumped into the excavation, and spread with a D-4 crawler tractor. Nuclear density tests, DCP tests, and moisture-content samples were then taken in the center lane of each item. Compaction lanes were then delineated on the surface of the test section with string lines, after which six passes were made in each lane with the impact compactor.

21. The basic tracking pattern used for compaction is shown in Figure 10. With this pattern, outside lanes were compacted on the first two

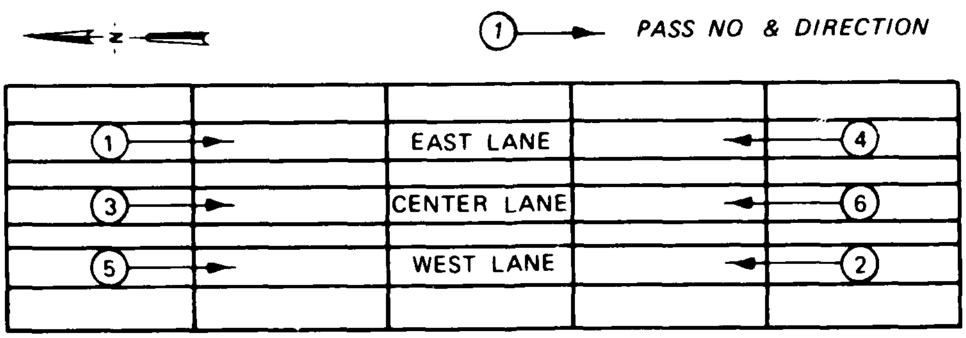


Figure 10. Tracking pattern, Test Section No. 2

passes, and the center lane was compacted on the third pass. The fourth and fifth passes were then applied to the outside lanes and the sixth pass to the center lane. Thus, one application of this pattern constituted a total of six passes to the test section, or two passes per lane. As can be seen from

Figure 10, alternate passes in each lane were applied in opposite directions. The overall pattern was then repeated three times so that a total of six passes was applied in each lane. After compaction, field soil data were again obtained in the center lane of each item. Next, shoulder areas were built up on each side of the original test section to a height of approximately 2.5 ft above the elevation of the original test area. The space between shoulders was about 26 ft and extended over 125 ft in length to provide for placement of the second lift. Again, the soil for each test item was transported to the site, dumped, and then spread with a crawler tractor. Enough width was provided on each shoulder so that after placement of the test soils, which were flush with the shoulders, there was sufficient test and shoulder area to allow for some lateral maneuver or wander of the tow tractor and compaction equipment. In-place soil data were then obtained on the center lane of each item after which test lanes were then designated on the surface and each lane received six passes of the impact compactor, as described previously.

22. Field soil data. Field data taken during the course of the test included in-place soil density and water content, surface-elevation readings, and DCP readings. For each of the two soil lifts, data were taken immediately after the soil was placed and again after completion of compaction.

23. As indicated, data were taken only in the center lane since this lane would be more representative of a conventional field-compa ted area while the outside lanes would represent peripheral or boundary conditions.

24. Soil-density data were obtained in the limestone by the water balloon method and in the other soils by nuclear meter method with drive-cylinder correlations. All water contents were obtained by the oven-drying method. Density and water content data were taken at 12-in.-depth increments. Surface elevation data were taken before and after compaction of each lift to determine cumulative settlement or consolidation. DCP data were obtained by driving the penetrometer into the soil with an 8-kg hammer and recording the depth of penetration. Penetration readings were obtained after each 5 blows of the hammer for most of the penetration tests; however, for the tests on the first lifts of items 1 and 2, 10-blow increments were used. Generally, it was attempted to develop penetration to a depth of 1,000 mm.

PART III: TEST RESULTS AND DISCUSSION

Test Results

Test Section No. 1

25. Visual observations. No unusual occurrences were observed during operation of the vibratory roller. It was noted, however, that possibly some precompaction had developed in some of the soil lifts during spreading operations with the crawler tractor, as evidenced by the small amount of settlement.

26. Surface measurements. Surface-elevation data were taken along the centerline of the test lane on each lift at 2-ft intervals before and after compaction. These data are presented in Table 1. Representative profiles, shown for the fourth and eighth lifts, are presented in Figures 11 and 12, respectively. To establish some measure of surface settlement, mean values of surface elevation for each item along with the standard deviations from the mean were calculated. The difference in mean elevations before and after compaction provides some indication of soil consolidation. The standard deviations provide some measure of the profile variance. These data are presented in Table 2.

27. A summary of the mean elevation differences for each item along with the total mean elevation differences is also shown in Table 3. In item 1, mean differences in elevation, in the debris before and after compaction, varied from a minimum of 0.3 in. to a maximum of 0.9 in., with an average of 0.6 in. and a total of 3.4 in. In the crushed limestone, the mean and total values were 1.1 and 2.1 in., respectively. The mean elevation differences in item 2 ranged from 0.1 to 0.4 in. with an average of 0.3 in. and a total of 2.2 in. In item 3, the minimum and maximum values of elevation differences were 0.3 and 0.7 in., respectively, and the average difference was 0.5 in. Total value was 4.2 in. The values of mean elevation differences in item 4 ranged from 0.5 to 1.1 in. with an average elevation difference of 0.9 in. and a total of 7.4 in. In item 5, the mean differences varied from a minimum of 0.4 to a maximum of 1.0. The average of the values was 0.7 in. and the total was 5.7 in.

28. In-place soil density and water content. Values of in-place soil density and water content before and after compaction are shown in Table 4. The values shown are the means of three values obtained at the depth indicated.

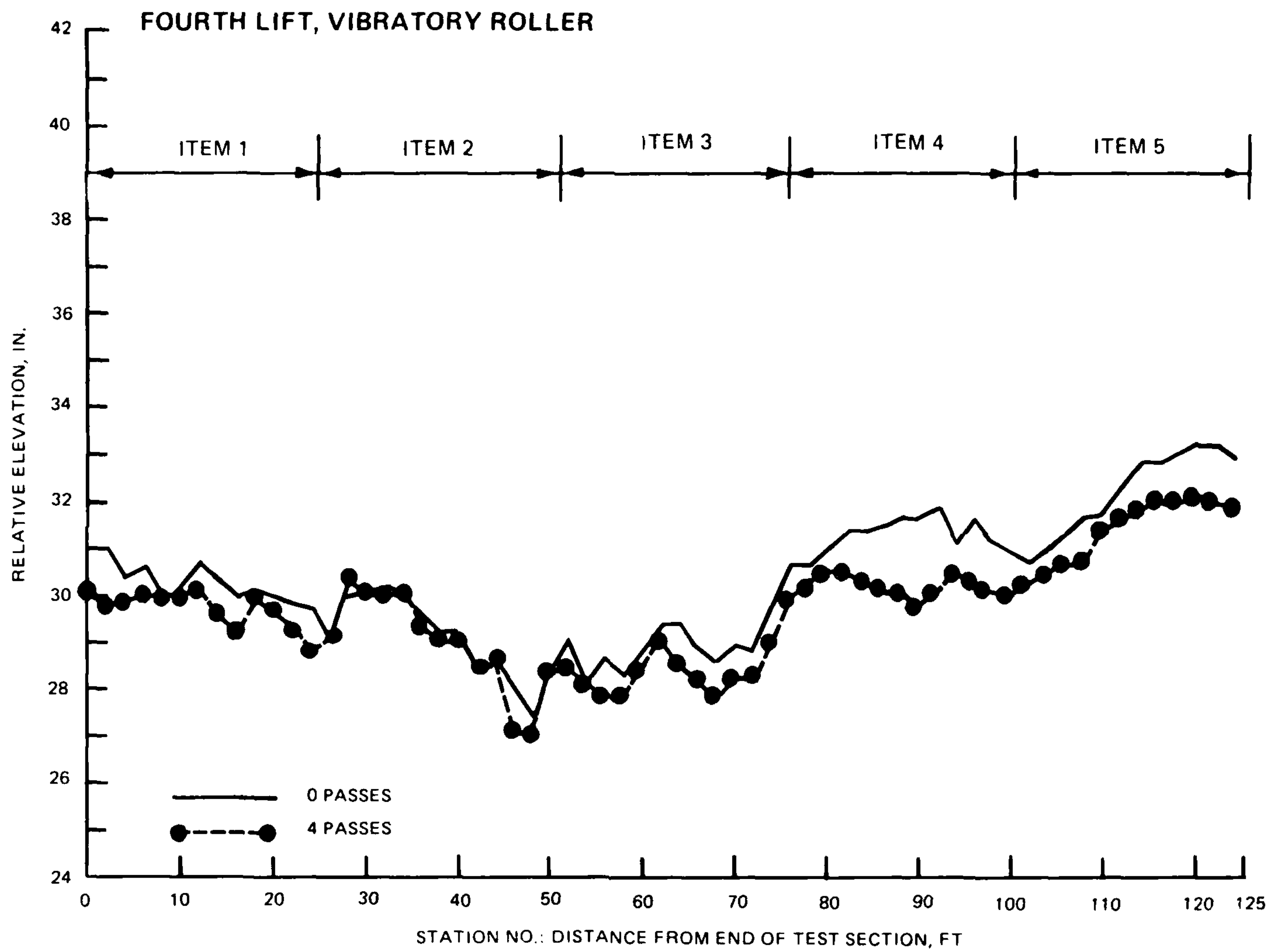


Figure 11. Surface elevation profile, lift 4, lane 1

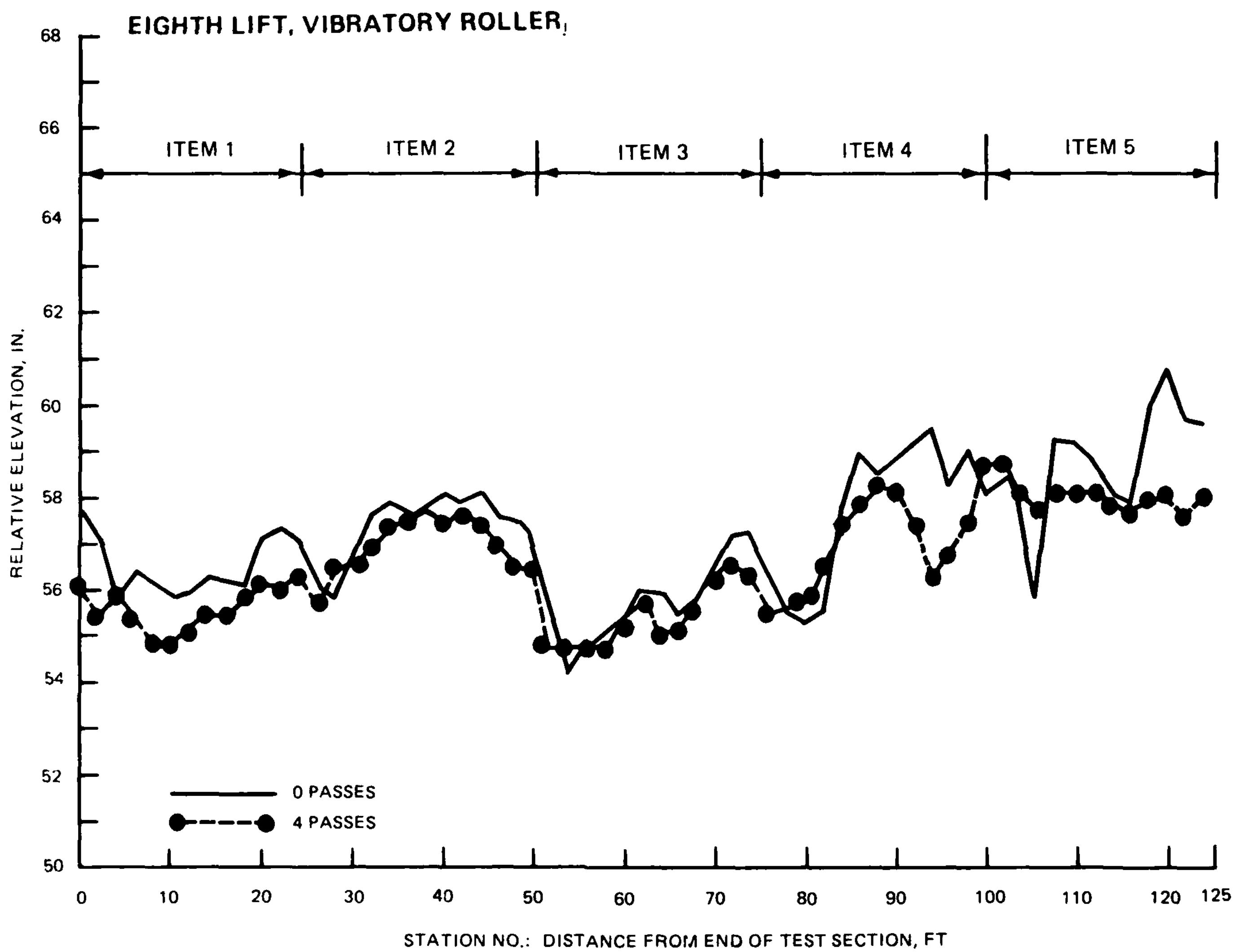


Figure 12. Surface elevation profile, lift 8, lane 1

These data are also plotted to indicate density profile in Figure 13. Although data were taken prior to compaction in each individual lift, the values shown in Table 4 are based on calculated locations or depths for which comparable data were taken after compaction. The data are so presented to provide a basis for comparison of the precompaction and postcompaction soil states. In addition to the absolute values shown in Table 4, density is also presented in terms of percent of the maximum laboratory CE-55 density. As indicated earlier, the maximum laboratory density values for the limestone, gravelly sand, and sand tailings were taken at near-zero water content but those for the silty clay and river sand were taken at optimum moisture content. Only the lean clay was actually compacted near the conventional optimum water content; therefore, it would be conceivable that the maximum CE-55 density could be attained with this soil. Similarly, the crushed limestone was compacted at a very low moisture content, and high density should also be attainable with sufficient compaction. In the other soils, however, since the field-water contents were essentially in the bulking range, the maximum density practically attainable would be less than the maximum CE-55 density. In keeping with convention, however, in-field in-place density values indicated in Table 4 are expressed as a percentage of the maximum CE-55 densities.

29. In item 1, the average density for the 12 in. of crushed limestone before and after compaction was 115.5 and 126.6 lb/cu ft, respectively. This represents an increase of from 87.2 percent to 95.6 percent of the maximum CE-55 density. Average water content after compaction was 2.6 percent. The average density of the debris material after compaction (i.e. the mean of the density values at 24, 36, and 48 in.) was 128.0 lb/cu ft. In item 2, lean clay, the average density for the upper 48 in. of soil before and after compaction was 99.8 and 103.9 lb/cu ft, respectively. The increase in density was from 86.3 to 90.0 percent. The average water content after compaction was 14.6 percent, which is slightly below the optimum water content for the soil. In item 3, compaction data for the river sand indicate precompaction and postcompaction densities of 99.8 and 107.4 lb/cu ft, respectively, representing an increase from 84.8 to 91.3 percent. The average postcompaction water content was 6.4 percent. In item 4, gravelly sand, average soil density before and after compaction was 102.0 and 115.3 lb/cu ft, respectively, which was an increase from 84.5 percent to 95.5 percent. It should be noted, however, that the surface density value, 109.8 lb/cu ft, was considerably lower than the

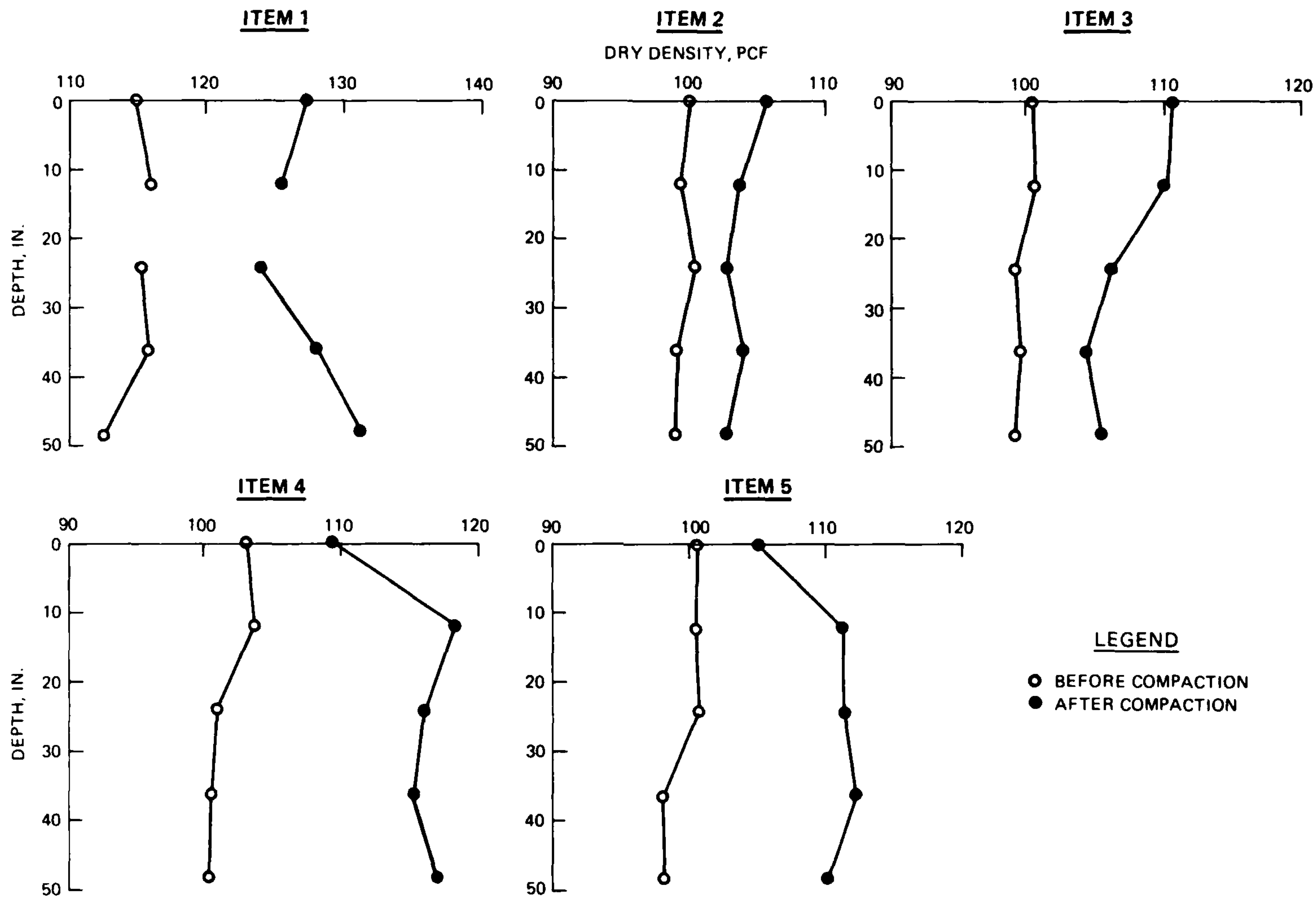


Figure 13. Density profiles, lane 1

other densities. Average water content after compaction was 4.1 percent. In item 5, the density values for the sand tailings before and after compaction were 99.7 and 110.2 lb/cu ft, respectively. These values reflect an increase in density from 88.3 percent to 97.5 percent. In this item, the surface density, 105.1 lb/cu ft, was also lower than the other density values. The average water content after compaction was 9.2 percent.

30. Density profiles are shown in Figure 13. In item 1, there was a slight decrease in density of the crushed limestone after compaction from the surface to the 12-in. depth. In the debris material, the density profile indicates lower densities in the upper lifts. The density profile for item 2 indicates a relatively uniform density for the depth sampled. For item 3, the density profile after compaction shows a decrease in density at the 24-, 36-, and 48-in. depths. In item 4, as was indicated earlier, the surface density after compaction was less than the density values at the 12- through 48-in. depths; however, the profile indicates uniformity of density below the 12-in. level. The density profile for item 5 after compaction also indicates a lower density value at the surface with fairly uniform densities below the surface.

DCP

31. A description of the DCP is given in Appendix A. DCP readings were obtained after placement of lifts 1-4 and again after placement of lifts 5-8. These data are shown in Table 5. Penetration readings were taken at 10-blow increments in lifts 1-4 of items 1, 2, and 3, and in 5-blow increments for lifts 1-4 of items 4 and 5, and for lifts 1-8. Correlations have been presented in other studies between DCP and California Bearing Ratio (CBR); however, CBR was not used as an evaluation parameter in the study. No satisfactory correlation was found between soil density and DCP readings.

Production rate

32. Production rate of the vibratory compaction is based on the following:

Effective compaction width: 7 ft (= drum width)

Operating speed: 328 ft/min

Lift thickness: 7.5 in. (0.625 ft)

Travel distance: 25 ft/pass

No. passes: 4

$$\text{Volume of compaction} = 7 \times 25 \times 0.625\text{, cu ft}$$

$$\text{Time of compaction} = \frac{25 \times 4\ \text{ft}}{328\ \text{ft/min}}\ (\text{min})$$

$$\text{Production rate} = \frac{\text{Volume of Compaction, cu ft}}{\text{Time of Compaction, min}}$$

$$= \frac{7 \times 25 \times 0.625}{(25 \times 4)/328}$$

$$= 358.8\ \text{cu ft/min}$$

Test Section No. 2

33. Visual observations. Observations noted during compaction operations focused primarily on differences in rotational effectiveness of the four-sided drum on the different soil types. Although the compactor was towed at the recommended speed (8 to 12 km/hr), there was a marked difference in the rotational velocity of the drum. Visually, it appeared that, while a constant rotational velocity was obtained on the crushed limestone and silty clay soils, there was some slippage of the drum on the three sandy soils. It would appear that drum slippage might have some effect on deep compaction and most certainly affect the upper layer density.

34. Surface measurements. Surface-elevation data were taken along the centerline of the center lane of each lift at 2-ft intervals before compaction and at 1-ft intervals after compaction. These data are presented in Table 6. These data are also shown in Figures 14 and 15 as line profiles. As can be seen from Figures 14 and 15, the surface profiles after compaction (particularly in the items consisting of sandy materials) have a distinctive sinusoidal configuration which is characteristic of the pattern that may develop on the soil surface with the impact roller. To establish some measure of surface settlement, the mean values of surface elevation for each item, along with the standard deviations from the mean, were calculated. The difference in mean elevations before and after compaction provides some indication of soil consolidation. The standard deviations provide some measure of the profile variance. These data are presented in Table 7.

35. In item 1, the first lift consisted of 3.5 ft of debris which consolidated an average of 3.3 in. With the second lift, 1-1/2 ft of crushed limestone indicated an average settlement of 1.1 in. The silty clay in item 2 indicated mean settlement values of 3.0 in. for the first lift and 2.3 in. for the second lift. In item 3, the mean settlement values for the first and

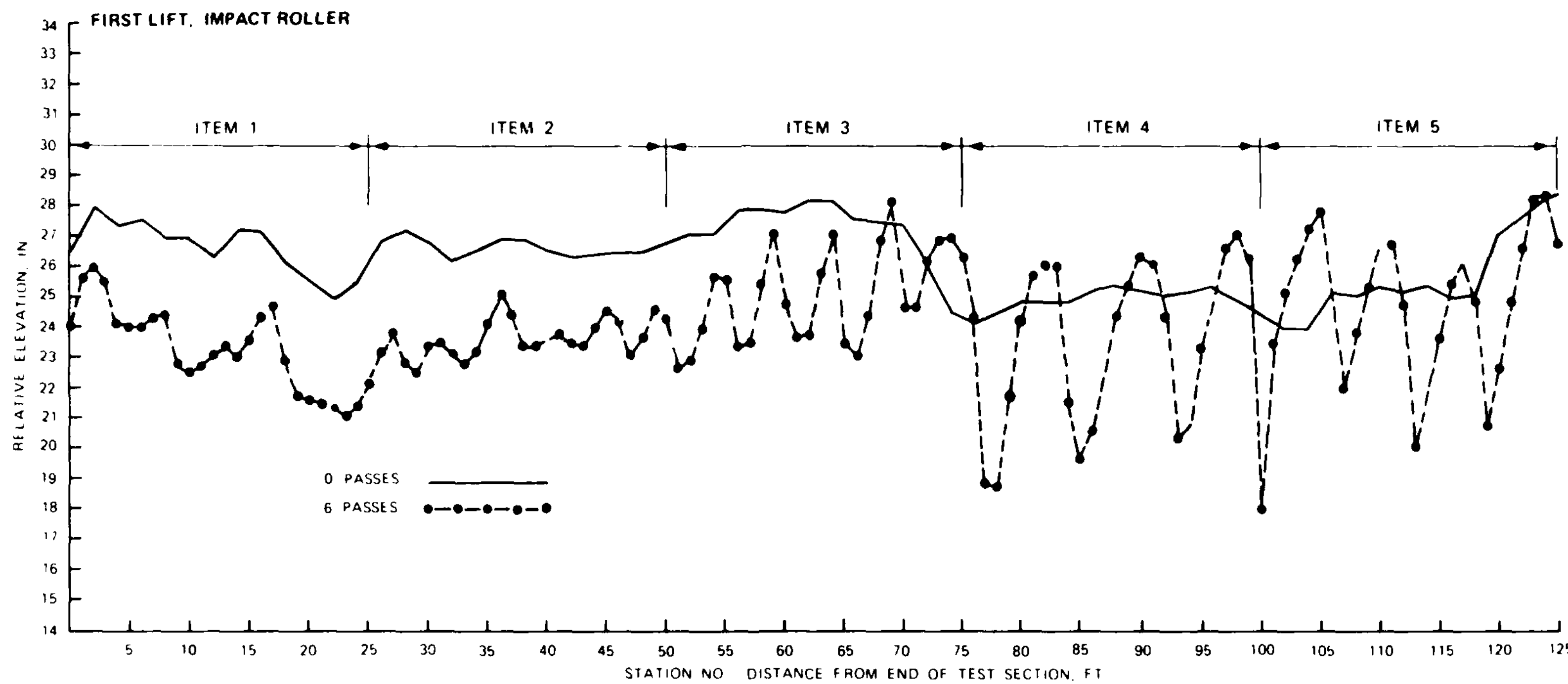


Figure 14. Surface elevation profiles, lift 1, lane 2

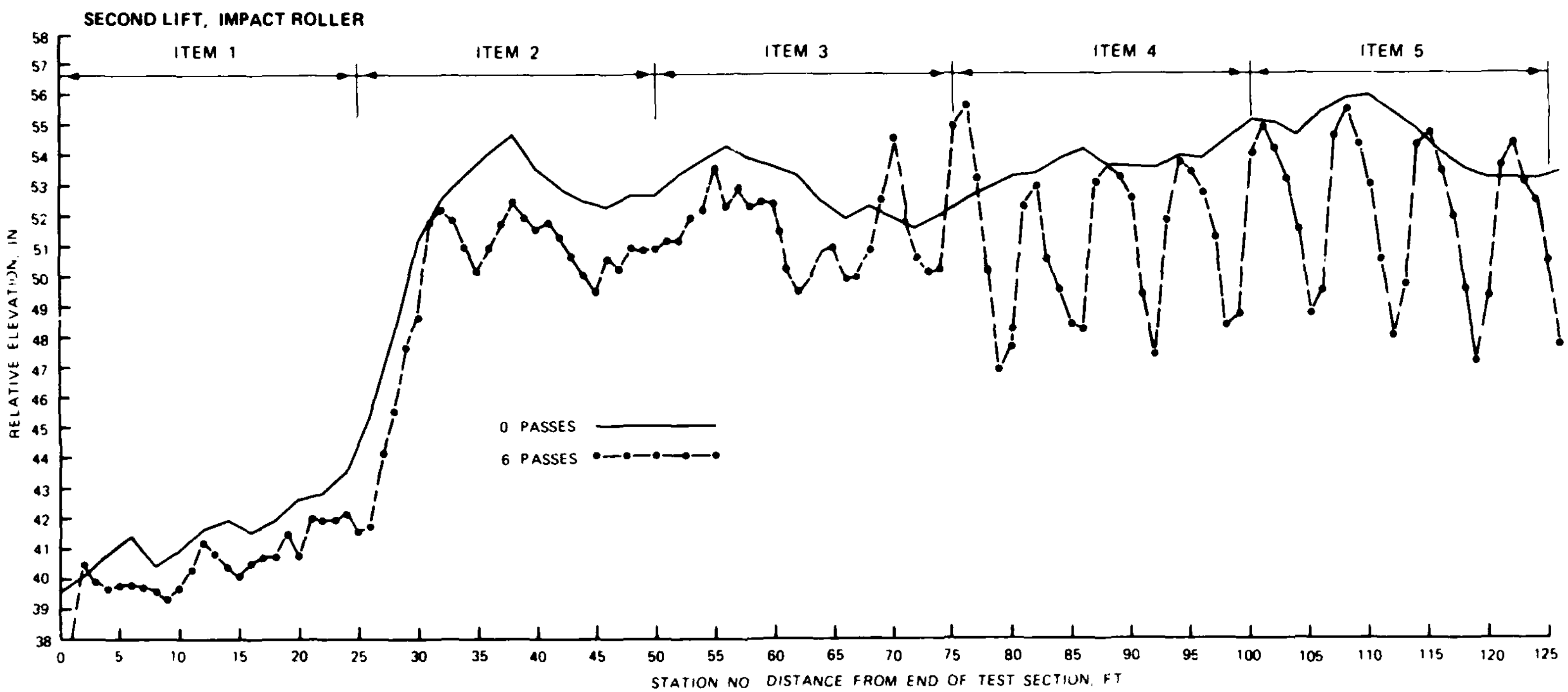


Figure 15. Surface elevation profiles, lift 2, lane 2

second lifts were 2.2 and 1.4 in., respectively. In item 4, the mean settlement values for lifts 1 and 2 were 1.2 and 2.4 in., respectively. In item 5, the first lift indicated only about 0.6-in. settlement while the second lift had a mean settlement of about 2.3 in. Excluding item 1 which had heterogeneous layers, the total mean values of settlement for both lifts in items 2, 3, 4, and 5 were 5.3, 3.6, 3.6, and 2.9 in., respectively.

36. In-place soil density and water content. Values of soil density and water content for each lift before and after compaction are shown in Table 8. The values shown are the means of three values obtained at the depth indicated. These data are also plotted to indicate the density profiles in Figure 16. In addition to the absolute values shown in Table 8, density is also presented in terms of percent of the maximum laboratory CE-55 density. Average values for the entire lift are also indicated. As indicated earlier, the maximum laboratory density values for the limestone, sandy gravel, and sand tailings were taken at near-zero water content, whereas those for the silty clay and river sand were taken at optimum moisture content. Only the lean clay was compacted near the conventional optimum water content; therefore, it would be conceivable that the maximum CE-55 density could be attained with this soil. Similarly, the crushed limestone was compacted at a very low moisture content, and high density should also be attainable with sufficient compaction. In the other soils, however, since the field-water contents were essentially in the bulking range, the maximum density practically attainable would be less than the maximum CE-55 density. In keeping with convention, however, the field in-place density values indicated in Table 8 are expressed as a percentage of the maximum CE-55 densities.

37. In item 1, the lower lift was debris material which had an average density of 110.3 lb/cu ft before compaction and 121.7 lb/cu ft after compaction. The average water content after compaction was 9.9 percent. The average density of the crushed limestone in the upper lift before and after compaction was 111.3 and 132.0 lb/cu ft, respectively, which represented an increase of from 84.0 percent to 99.7 percent of the maximum CE-55 laboratory density. Average water content after compaction was 1.2 percent. Average density of the debris material after compaction of the second lift (limestone) was 122.6 lb/cu ft. It should be noted that the material at the 24-, 36-, and 48-in. depths received the benefit of additional compaction applications.

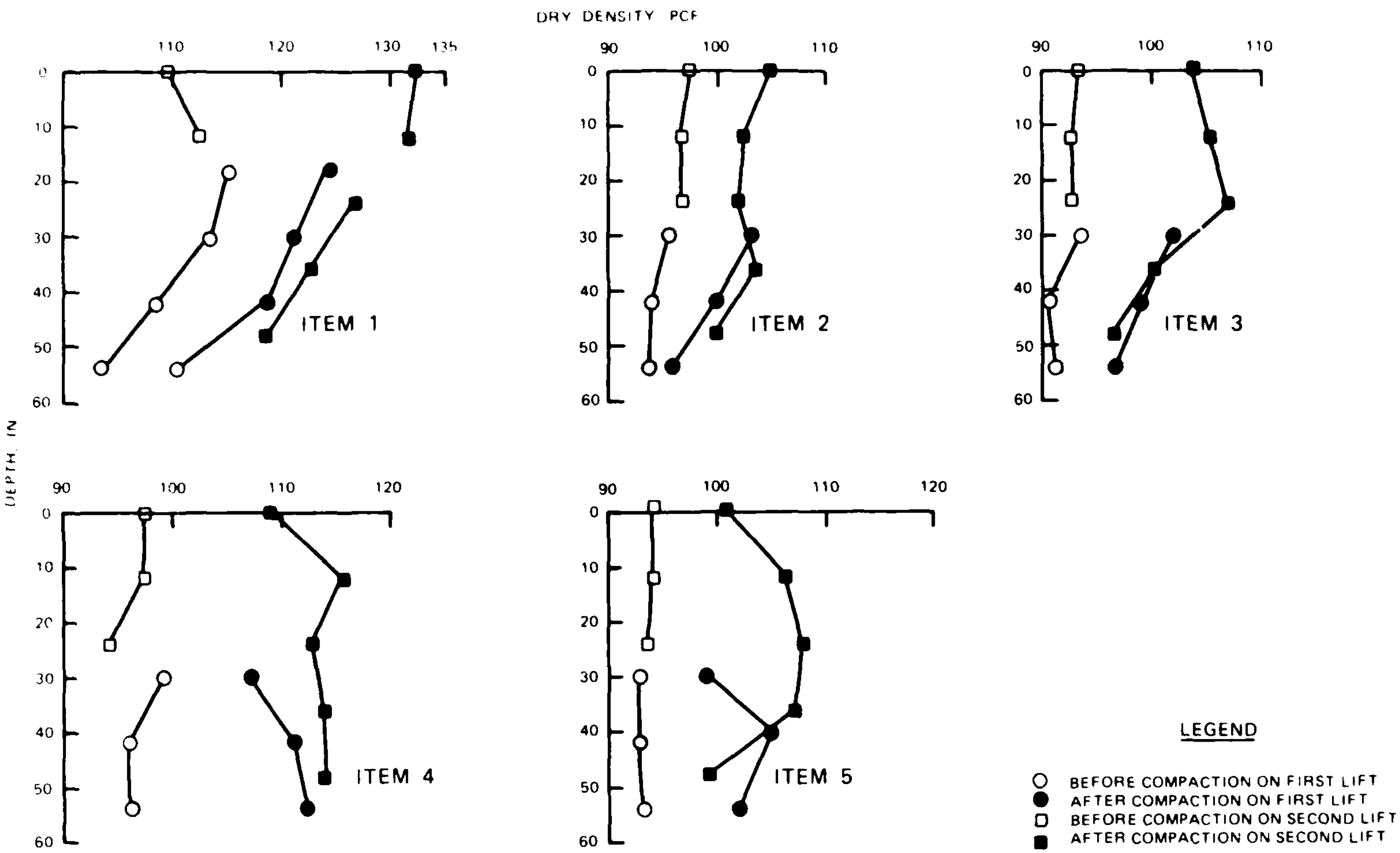


Figure 16. Density profiles, lane 2

38. In item 2, the silty clay, the average density of the lower lift before and after compaction was 94.7 lb/cu ft and 99.8 lb/cu ft, respectively. Water content after compaction was 15.6 percent. Density values represent an increase from 82.0 to 86.4 percent of the CE-55 maximum density. In the second or upper lift, the average precompaction and postcompaction densities were 97.1 and 102.4 lb/cu ft, respectively, for an increase from 84.1 to 88.7 percent of the maximum CE-55 density. Water content was 14.2 percent. In item 3, river sand, there was an increase in average density of the first lift from 91.9 to 99.5 lb/cu ft, or from 78.1 to 84.5 percent. Water content was 7.1 percent. In the second lift, precompaction and postcompaction average density was 93.1 and 102.6 lb/cu ft, respectively, representing an increase from 79.1 to 87.2 percent, respectively. Water content after compaction was 7.4 percent. Average densities in the first lift of item 4, gravelly sand, showed an increase from 97.3 to 110.5 lb/cu ft, respectively, or from 80.7 to 91.6 percent of the maximum CE-55 density. After-compaction water content was 5.2 percent. For the second lift the increase in average density was from 97.3 to 113.0 lb/cu ft, or from 79.9 to 93.6 percent. Water content after compaction was 5.8 percent. In item 5, average densities in the first lift before and after compaction were 93.1 and 102.2 lb/cu ft, respectively, representing a density increase from 82.4 to 90.5 percent. Postcompaction water content was 3.2 percent. In the second lift, the average density change was from 93.1 to 104.3 lb/cu ft, representing an increase from 83.3 to 92.3 percent of the maximum CE-55 density. After-compaction water content was 3.2 percent.

39. Density profiles are shown in Figure 16. In item 1, there was a relatively uniform increase in density in the first lift after initial compaction. In addition, there was a further slight increase in density in this material after compaction of the crushed limestone which composed the second lift. The density gradient indicates a decrease in density with depth from the 24- to 48-in. depth in the debris material both before and after compaction. The density profile for the crushed limestone reflects a fairly significant and uniform increase in density in the upper 12 in. of this material as a result of compaction. In item 2, the precompaction density profiles indicate relatively uniform density values for both lifts. The density profile for the first lift after initial compaction reveals a larger increase in densities at the surface (30-in. depth on the plot) than at the lower elevation.

The density profile for postcompaction on the second lift indicates a general increase in density in this lift, i.e. from 0 to 24 in. with a slight increase in density at 36- and 48-in. depths. The profile suggests that there was little change in density near the interface of the first and second lifts, i.e. at about the 3-in. depth. In item 3, the precompaction profiles indicate a slightly decreasing density gradient with depth in the lower or first lift and a uniform density in the upper or second lift. The after-compaction profile for the first lift reveals a significant general increase in density, with a larger increase in the upper elevation than at the lower levels. The profile after compaction of the second lift indicates significant increase in density in this lift down to the 24-in. level. The profile in the region also demonstrates a slightly increasing density-depth gradient. Below the 24-in. depth there is a sharp decrease in the density-depth gradient. The density value indicated for the 48-in. depth appears to be slightly less after compaction; however, this is possibly due to sampling variation. In item 4, density profiles prior to compaction of each lift indicate a decrease of density with depth. The postcompaction profile for the first lift indicates a general increase in density in that lift but also shows increasing density with depth. The density profile after compaction on the second or upper lift reveals a very large general increase in density from the surface to 24 in. with the largest increase being at the 12-in. depth. The profile also shows density values at the 24-, 36-, and 48-in. depths to be about equal, with a very slight increasing density-depth gradient. There also appears to have been some increase in density in the first lift. In item 5, the precompaction density profiles for both lifts indicate uniform values of about the same magnitude. The postcompaction profile for the first lift indicates a general increase in density in that lift; however, the density increase at the surface (30-in. depth in the plot) was markedly lower than at the lower elevations. The profile on the second lift after compaction indicates a large general increase in density at the surface, 12-, and 24-in. depths in the second lifts. However, the surface density value is the lowest of the three values. The density data at 48 in. also indicate a lower density value after compaction, but again this is possibly due to sampling variations.

DCP

40. DCP readings were obtained in each lift before and after compaction. These data are shown in Table 9. Penetration readings were taken at

10-blow increments prior to compaction in items 1 and 2 of the first lift and at 5-blow increments thereafter. As indicated earlier, other studies have presented correlations of DCP and CBR; however, CBR was not used as an evaluation parameter in the investigation, and no satisfactory correlation was found between soil density and DCP.

Production rate

41. The production of the impact roller is based on the following:

Effective compaction width:	7 ft (= 4.27-ft drum width + 2.73 ft between drum lanes)
Operating speed:	700 ft/min
Lift thickness:	2.5 ft
Travel distance:	25 ft/pass
No. passes:	6

$$\text{Volume of compaction} = 7 \times 25 \times 2.5\text{, cu ft}$$

$$\text{Time of compaction} = \frac{6 \text{ passes} \times 25 \text{ ft/pass}}{700 \text{ ft/min}} \text{ (min)}$$

$$\text{Production rate} = \frac{\text{Volume of Compaction, cu ft}}{\text{Time of Compaction, min}}$$

$$= \frac{7 \times 25 \times 2.5}{(6 \times 25)/700}$$

$$= 2041.7 \text{ cu ft/min}$$

Analysis and Discussion

Analysis

42. The primary objective of this study was to investigate means of compacting soils at- or near-zero water content with emphasis on desert-type materials. Two types of compactors were used in the study -- a single drum self-propelled vibratory roller and a towed-impact roller. Effects of compaction on the following five types of aggregate and soil materials were evaluated: crushed limestone, silty clay, and three types of sandy materials.

43. In attempting to process these materials to a state of near-zero water content, it quickly became apparent that, when working with large quantities of material, such a task is extremely difficult to achieve. In the case of the silty clay, it was finally determined that, under the climatic and

environmental conditions existing at that time, it would be infeasible to achieve a near-zero water content condition and, therefore, the soil was processed at optimum water content. Obviously, it is much easier to reduce the water content of soils that are free draining than it is to dry soils having high fines content. Therefore, in processing large quantities of soil, it would appear that the only efficient means of accomplishing this objective would be under climatic conditions of very low humidity preferably with a warm, dry prevailing wind.

44. During compaction operations with the impact roller, it was observed that rotational drum slippage occurred as the roller was towed over the sand materials. No significant slippage was observed in the crushed limestone and silty clay materials. Obviously, slippage reduces the impact effect of the drum and, therefore, would influence the efficiency of compaction. This difficulty might have been alleviated by use of a thin clay blanket placed on the surface of the sandy material to provide a gripping surface for the drum. However, the scope of this project did not allow further experimentation in this area.

45. A summary of the soil-density data indicating density values at 12-in. sampling increments before and after compaction, increase in density as a result of compaction, and ratio of increase in density to initial density (normalized value) is shown in Table 10. All density values are given in terms of percent of the maximum CE-55 laboratory density except for those for the debris material which are actual density values in lb/cubic foot. The before and after compaction density data and the normalized values are shown in bar graph form in Figures 17 and 18. These graphs clearly illustrate the initial and final density and the change in density.

46. In item 1, as shown in Figures 17a and 18a, the density value of the crushed limestone at the surface and 12-in. depths prior to compaction was higher in lane 1 than in lane 2. After compaction, however, the density was higher in lane 2 than in lane 1. Therefore, the overall density increase was larger in lane 2. In the debris material, density before compaction was also lower in lane 2 than lane 1 at 24-, 36-, and 48-in. depths. However, only at the 24-in. depth did the increase in density in lane 2 exceed that of lane 1. At the 36- and 48-in. depths the after-compaction density was higher in lane 1 than in lane 2. It would appear, therefore, that in this material, compaction

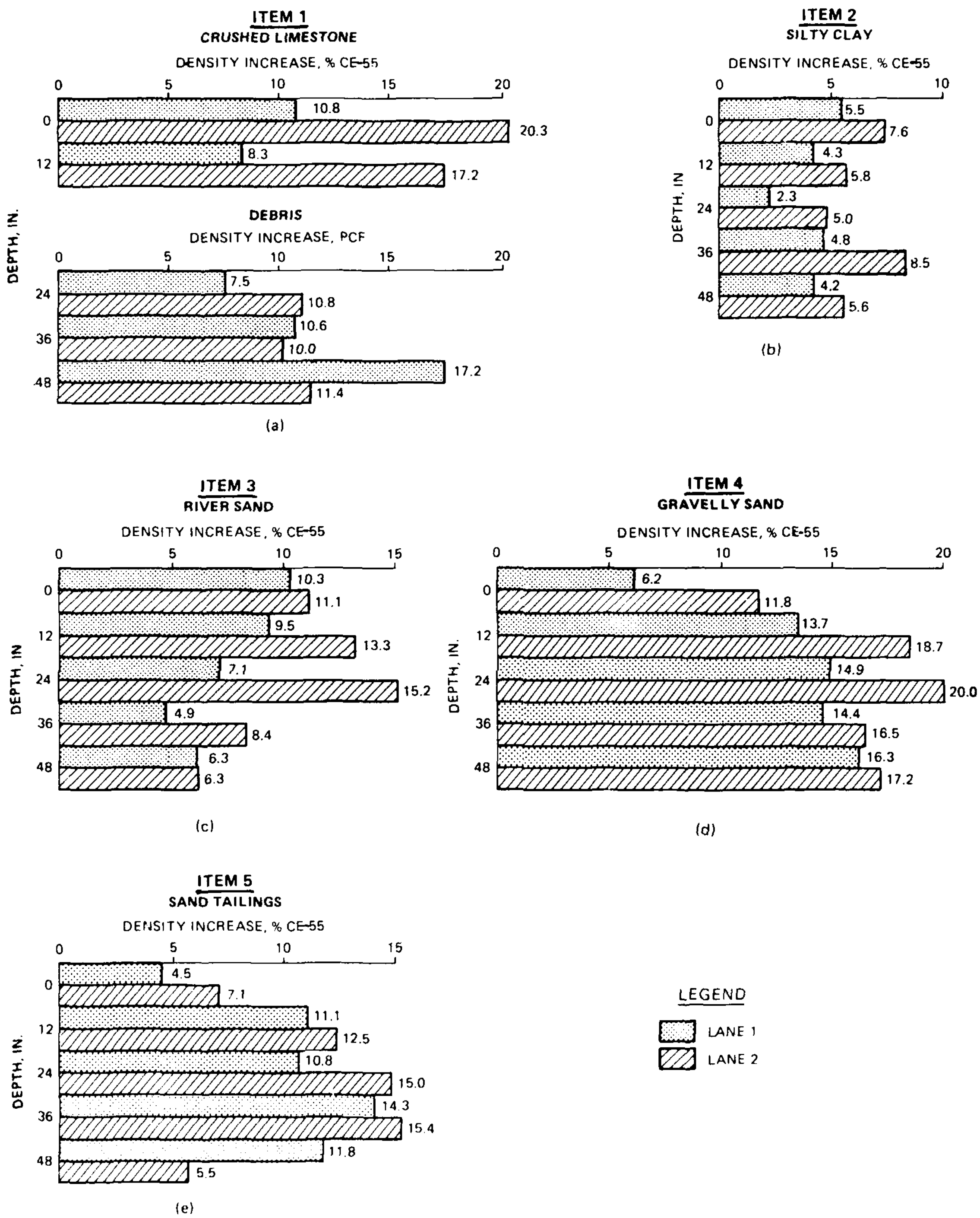


Figure 17. Precompaction and postcompaction density at depths indicated

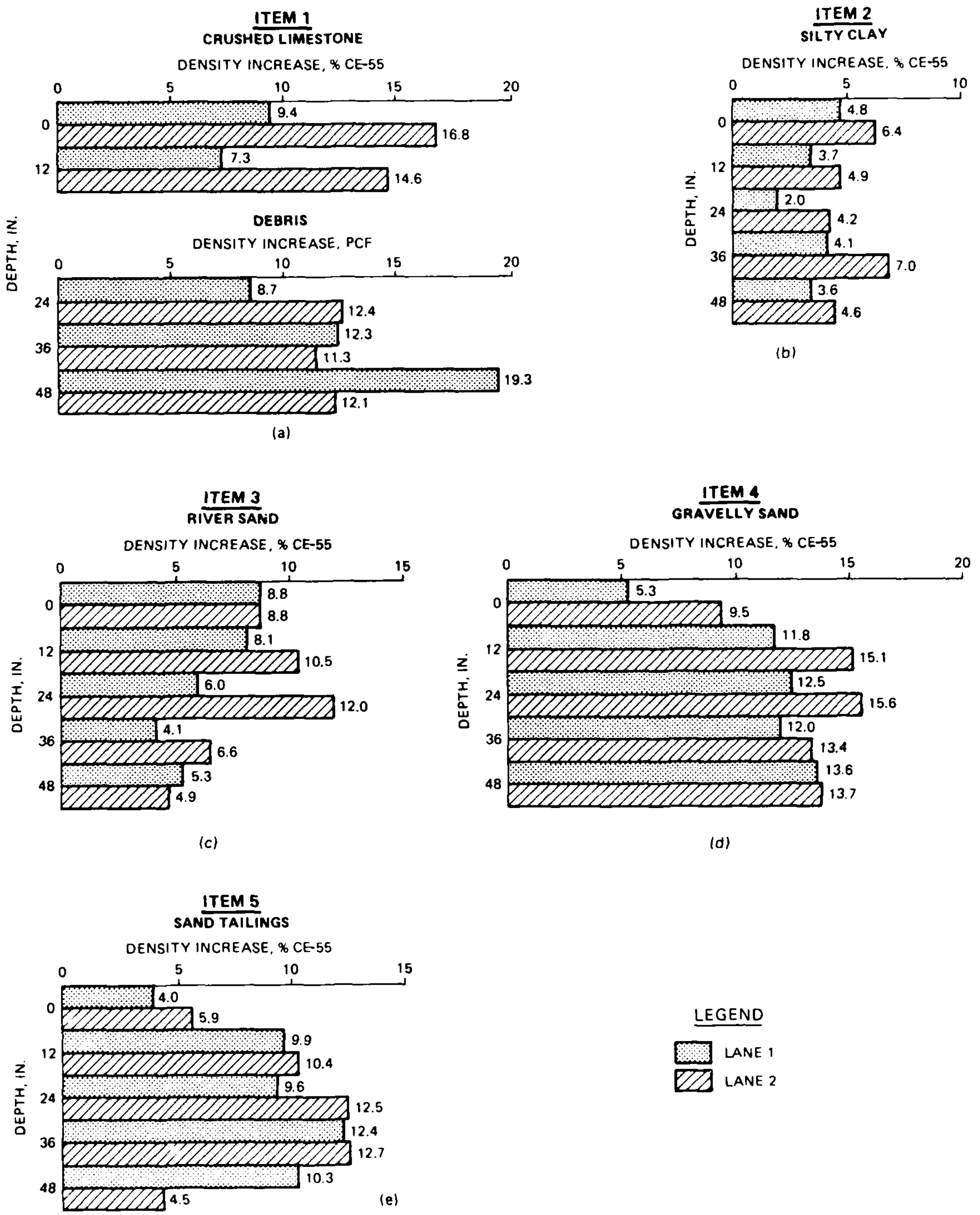


Figure 18. Density increase at depths indicated

in thin lifts (lane 1) gave better results than the thick lift compaction procedure (lane 2).

47. In item 2, Figures 17b and 18b, the density values in lane 1 were higher than those in lane 2 both before and after compaction at all sampling elevations. The relative increase in density was higher in lane 2 than in lane 1 at all depths.

48. In item 3, Figures 17c and 18c, the precompaction densities in lane 1 were considerably higher than those in lane 2. Postcompaction densities in lane 1 were also higher than those in lane 2 except, at the 24-in. depth, the density in lane 2 slightly exceeded that at lane 1. In lane 2, density increase values were higher at the surface and at 12-, 24-, and 36-in. levels and equal in both lanes at the 48-in. depth.

49. In item 4, Figures 17d and 18d, density values in lane 1 were higher than those in lane 2 both before and after compaction. Relative increase in density was higher in lane 2 than in lane 1.

50. In item 5, Figures 17e and 18e, precompaction densities were considerably higher in lane 1 than in lane 2. Densities after compaction were also higher in lane 1 than in lane 2, and, at the surface and 48-in. levels, the density in lane 1 before compaction was about equal to the postcompaction densities in lane 2. Relative changes in density indicate higher values for lane 2 at the surface and at 12-, 24-, and 36-in. depths, and a significantly larger value for lane 1 at the 48-in. depth.

51. Table 11 shows a summary of mean values of soil density for each material in each item before and after compaction, values of the increase in mean density and ratio of density increase to density before compaction (normalized values). The before and after compaction density data and the normalized value are plotted in bar graph form in Figures 19 and 20.

52. In item 1, the increase in average density for the crushed limestone was considerably higher in lane 2 than in lane 1. In the debris material, the average density after compaction was higher in lane 1, although the increase in average density was only slightly less in lane 2 than in lane 1. In item 2, the final average density was higher in lane 1, but the increase in average density was higher in lane 2. In items 3 and 4, the average density before and after compaction was lower in lane 2 than in lane 1, although the increase in density was larger in lane 2. In item 5, again the average

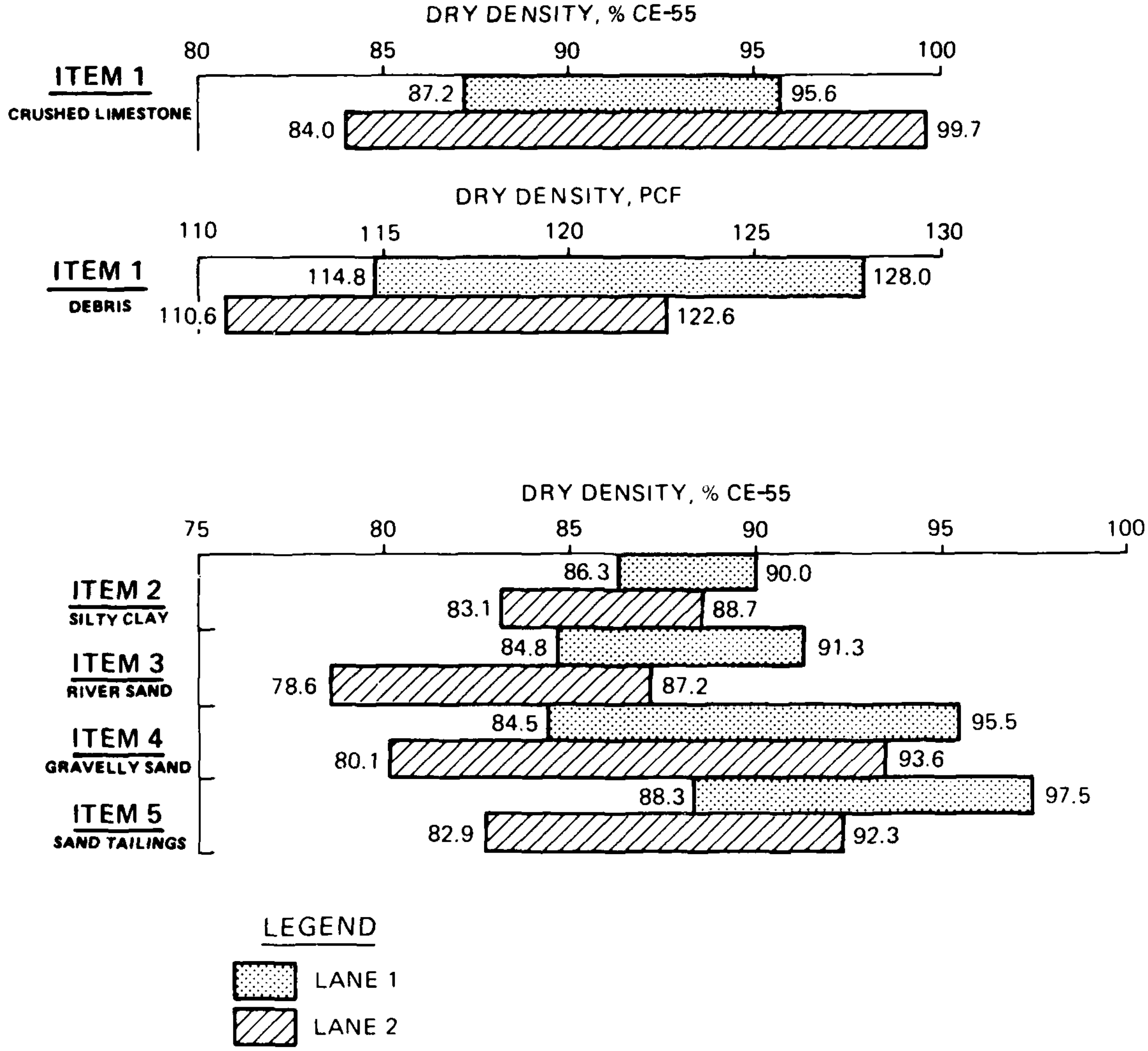


Figure 19. Precompaction and postcompaction density, mean values

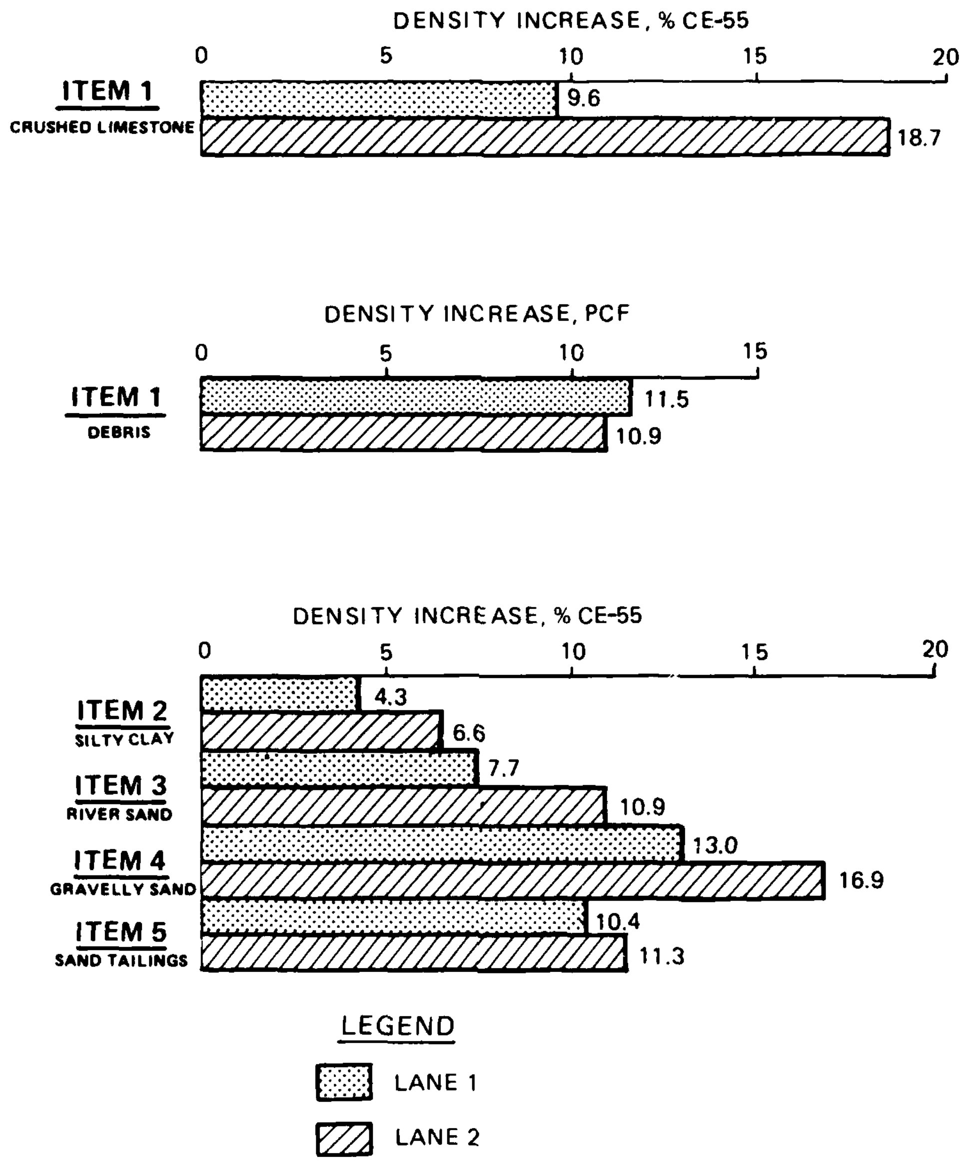


Figure 20. Density increase, mean values (normalized)

density before and after compaction was higher in lane 1, but the increase in density was slightly higher in lane 2.

53. The density values discussed previously have been expressed in terms of percent maximum CE-55 laboratory density. This is the conventional manner in which density specifications and field densities are expressed; however, the maximum density achievable for a given compaction effort is also a function of the soil-water content at the time of compaction. Therefore, the average field-density values before and after compaction were also computed in terms of percent of the laboratory CE-55 density based on the actual average field water content. These values, along with the actual and normalized density increase values, are given in Table 12. Density values before and after compaction and the normalized increase values are presented in bar graph form in Figures 21 and 22. A review of the recomputed values and comparison of them with the average density values based on the maximum CE-55 laboratory densities (Table 11 and Figures 19 and 20) indicates that the relative values of the densities in each lane are essentially unchanged, i.e. the difference between initial and final density in each item of each lane is about the same when computed by either standard. However, it is significant to note that four of the recomputed values (items 1, 4, and 5 of lane 1 and item 1 of lane 2) exceed 100 percent of the CE-55 laboratory density, and two values (items 4 and 5 of lane 2) exceed 98 percent. In the plastic materials (PI > 0), both compaction methods achieved about 90 percent of the density achievable by CE-55 compaction at the field-water content. All three of the nonplastic materials achieved more than 98 percent density by either method.

54. Another approach to evaluation of test results is to examine density increase with respect to change in compaction energy based on the laboratory moisture-density relations. First, the relationship between laboratory soil density (pound per cubic foot) and laboratory compaction effort (foot pound per cubic foot) is defined at the precompaction and postcompaction field-water content values. Using these relationships, compaction energy values corresponding to the field-density values before and after compaction may be determined. The difference between the precompaction and postcompaction energy values is thus used as a measure of compaction efficiency. It is realized that there is considerable difference between the dynamics of laboratory and field compaction; however, this approach provides a quantitative means for measuring compaction effectiveness.

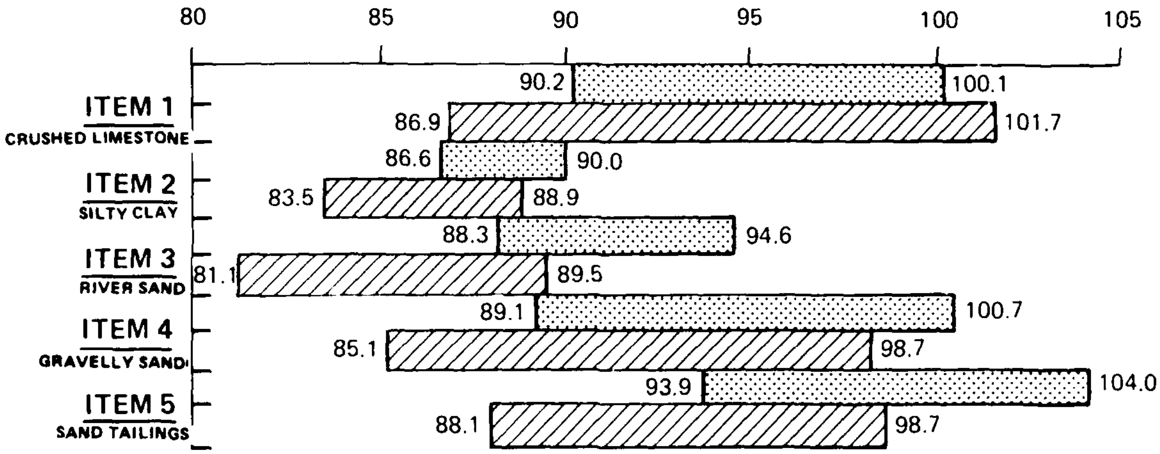


Figure 21. Precompaction and postcompaction density (percent CE-55) at actual water content

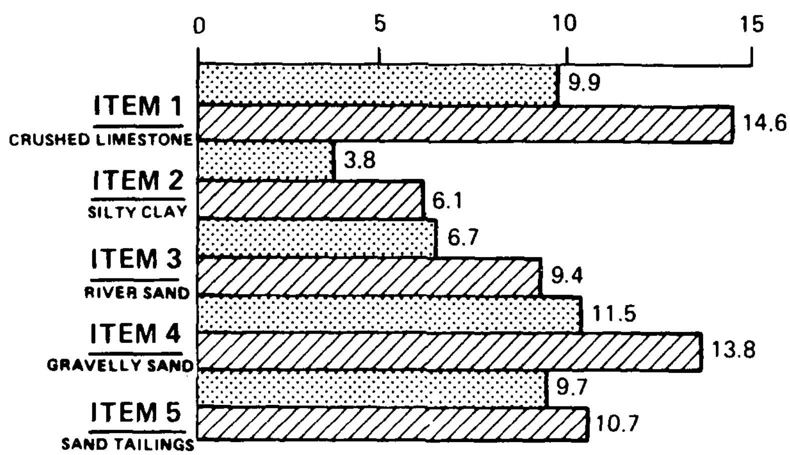


Figure 22. Density increase (percent CE-55) at actual field-water content (normalized)

55. A summary of soil density-compaction energy data is given in Table 13. Included are (a) mean field density and water-content values for each item before and after compaction, (b) laboratory density for the CE-12, CE-26, and CE-55-compaction efforts determined at the field water contents, (c) compaction energy values associated with the field densities before and after compaction, and (d) increase in compaction energy values. As an example, data for item 3, lane 1, are shown in Figure 23. From the laboratory compaction curves for the river sand (Figure 5), soil densities for the 12-, 26-, and 55-ft-lb/cu ft compaction efforts were determined at field water contents of 5.9 and 6.4 percent. These data are shown as semilogarithmic plots in Figure 23. Superimposing the precompaction density value of 99.8 lb/cu ft on the back-extrapolated precompaction plot, a compaction energy value of 8.0 ft-lb/cu ft is indicated. For the postcompaction plot, a density value of 107.4 lb/ cu ft indicates a compaction energy value of 22.0 ft-lb/cu ft, or an increase of 14.0 ft-lb/cu ft. Using this procedure, the increase in compaction energy values was determined for all test items. In cases where the back-extrapolated curve extended below a compaction energy level of 1 ft-lb/cu ft, an actual value of 1 was used. Computed values of compaction energy are shown in Table 13.

56. Comparisons of compaction energy increase values for each item are shown in bar graph form on Figure 24. Values indicated are the logarithms of the compaction energy increase values.

57. The bar graphs indicate higher values for lane 2 in items 1 and 2 and higher values for lane 1 in items 3, 4, and 5. These results indicate better compaction efficiency with the impact roller in the crushed limestone (PI = 0) and the silty clay (PI = 4); whereas, better efficiency was obtained with the vibratory roller in the river sand (PI = 5), sandy gravel (PI = 0), and the sand tailings (PI = 0).

58. Figure 25 shows the after-compaction density profiles for items 1-5 in both lanes. Profiles for the crushed limestone in item 1 and for items 2, 4, and 5 are similar for both lanes. In item 2, the density was generally uniform throughout the depth sampled. In item 4, density values were uniform from the 12- to 48-in. depths but were considerably lower at the surface. In item 5, densities were relatively uniform at the 12- to 36-in. depth but in both lanes density values at the surface and at 48 in. were low. Profiles for the debris material indicate opposing gradients increasing in lane 1 and

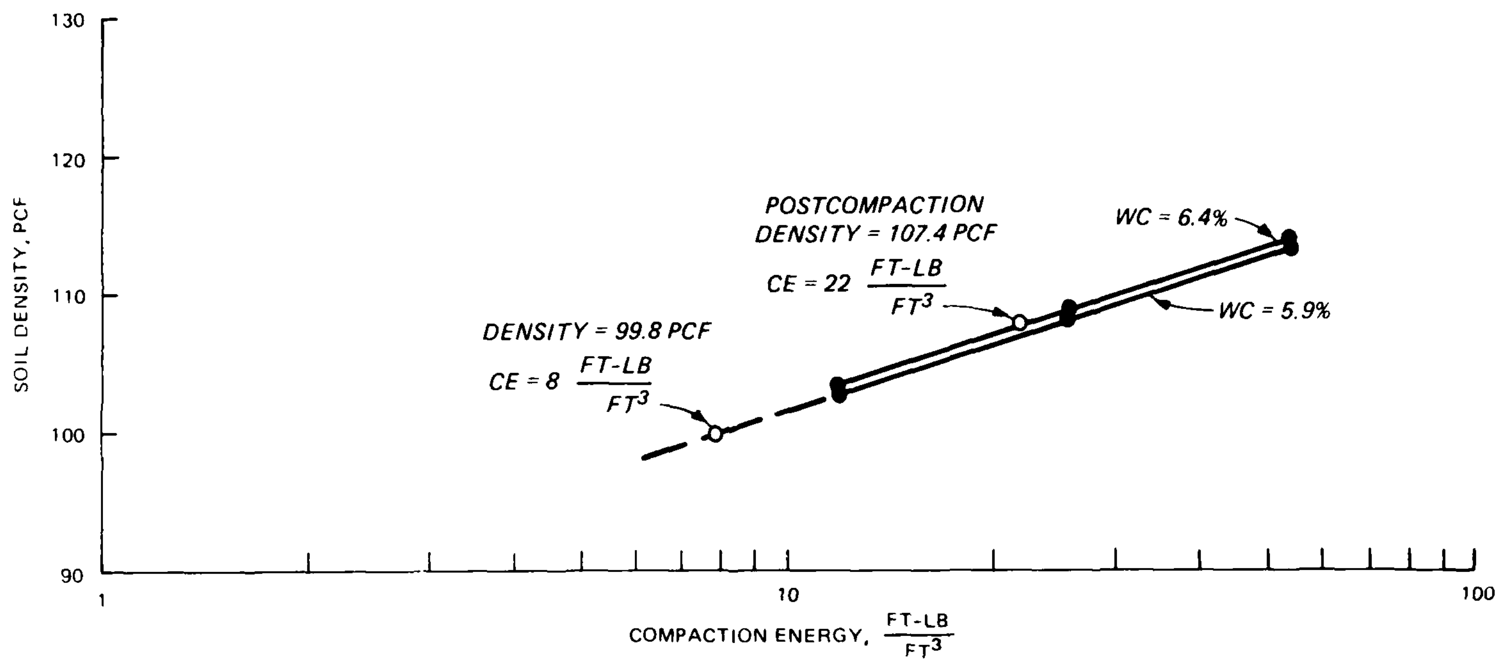


Figure 23. Compaction energy increase, item 3, lane 1

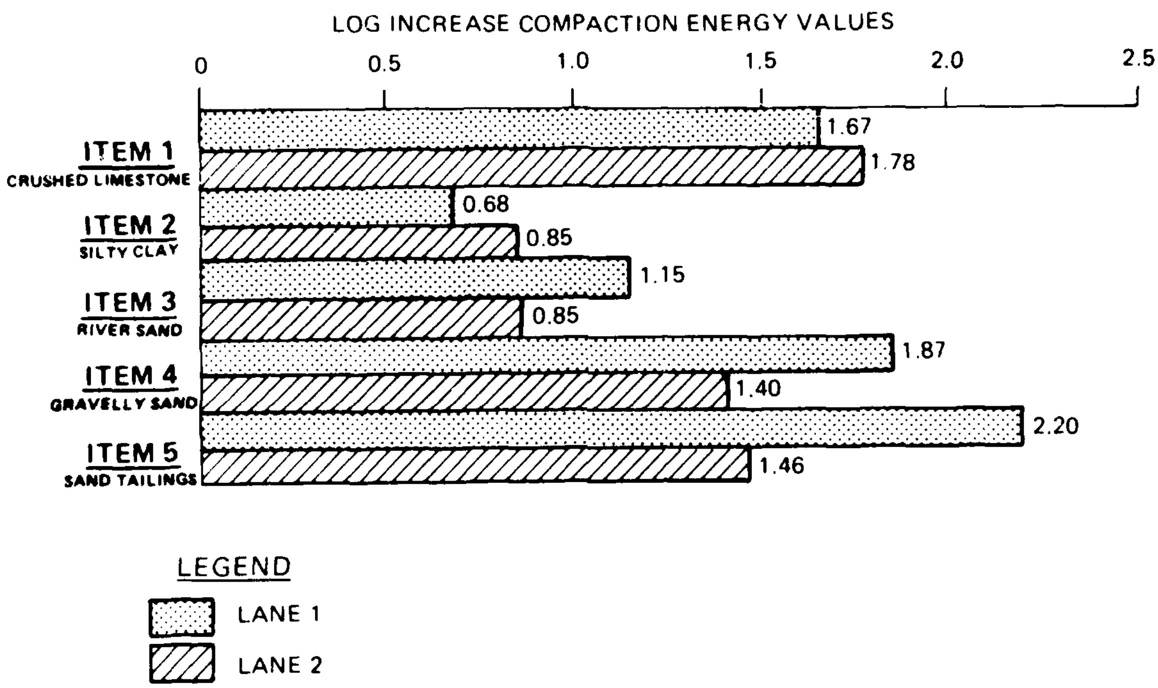


Figure 24. Compaction energy increase

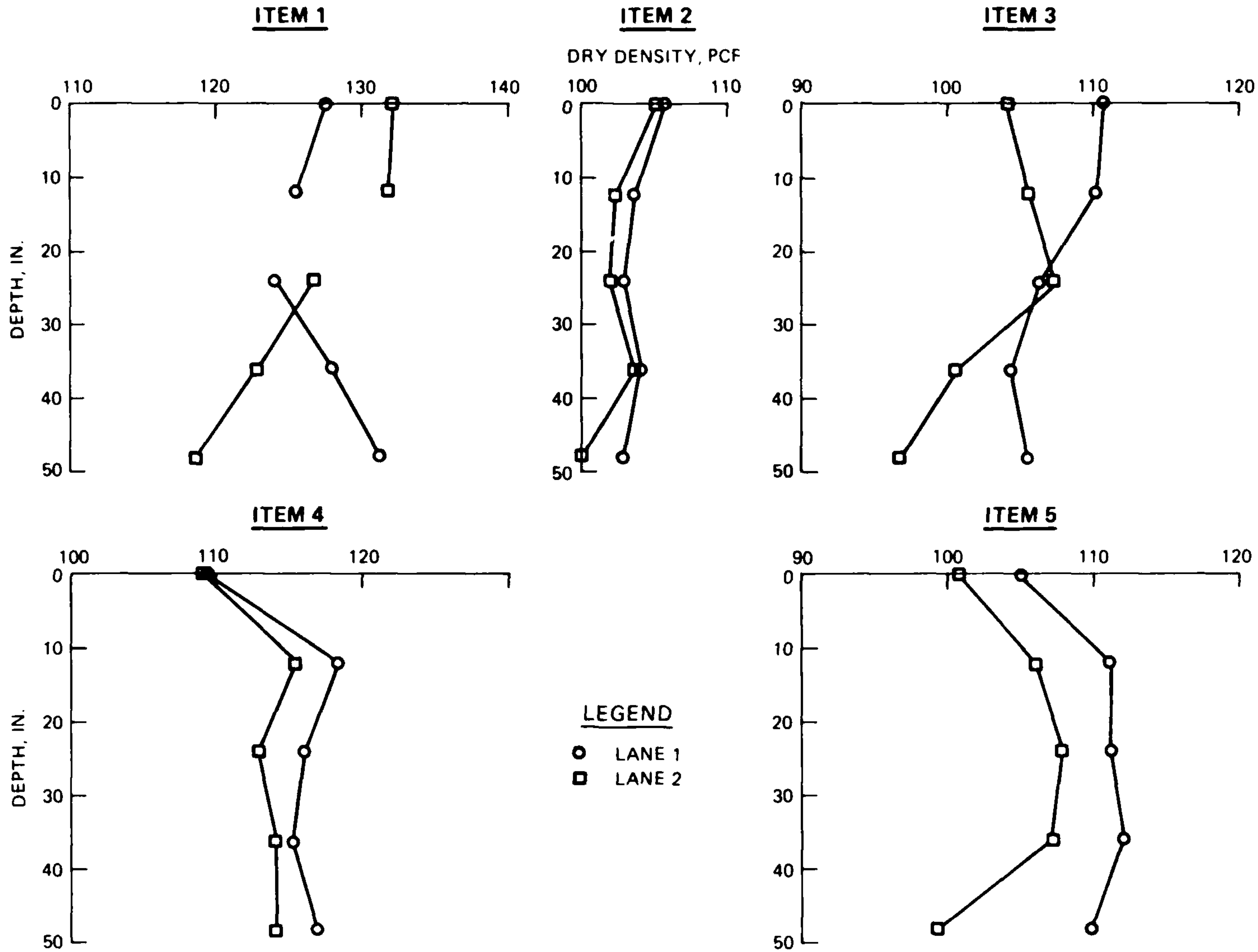


Figure 25. Postcompaction profiles

decreasing in lane 2. In item 3, the profile for lane 1 is somewhat erratic with the highest density value near the center of the sampling zone; whereas, the profile for lane 2 indicates a general decreasing density gradient.

59. Changes in surface elevation generally did not correlate well with density changes except in items 2, 3, 4, and 5 of lane 1. A summary of total mean surface elevation change, mean density change, and these values normalized against initial conditions is given in Table 14 (initial thickness is taken as 60 in.). Normalized values are shown plotted in Figure 26.

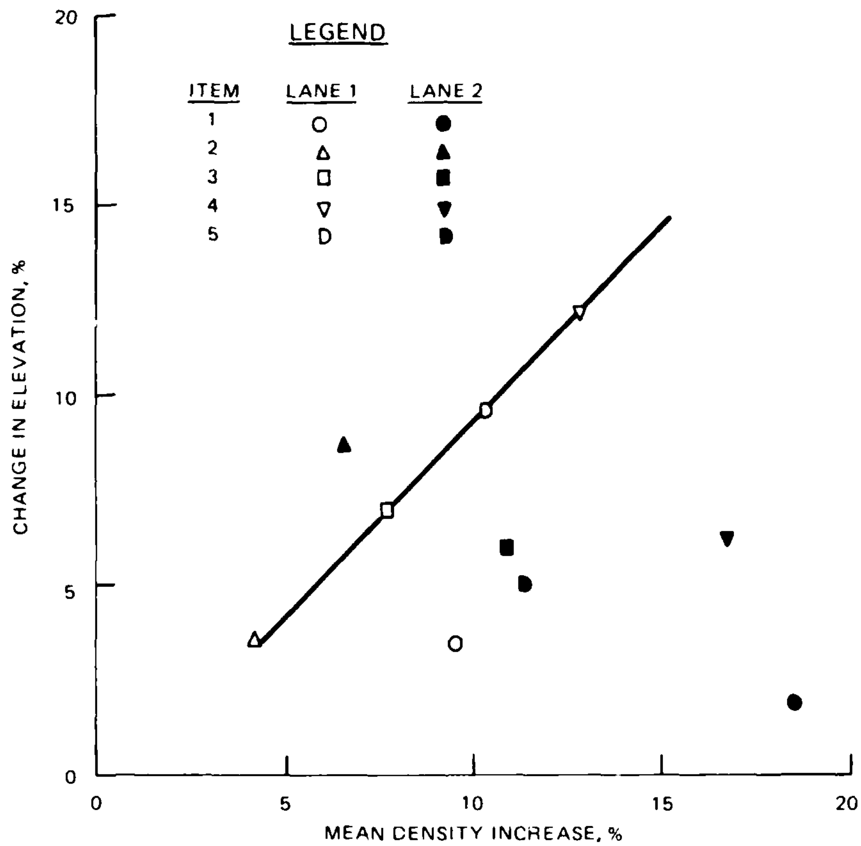


Figure 26. Mean density increase versus change in elevation

Discussion

60. In discussing the results of this investigaticn, several considerations should be reviewed. Although two different roller types were involved, the study was not intended to be a comparative performance evaluation of the equipment but to study different means of compacting soils at near-zero water content. Both types of equipment were operated in general accordance with manufacturers' recommendations. Test results indicate that satisfactory

performance could be obtained with either type of equipment, but the type of soil involved and procedures used in processing the material are also significant factors in an overall process.

61. The lowest overall densities in both lanes were obtained in the silty clay material (item 2). Generally, comparable results were obtained with both types of equipment. Difficulty in processing this material was readily apparent with the result that the conventional optimum water content was finally selected as the target value. Low plasticity soils of this type are often found in the desert regions, especially in the play areas, and, under arid climatic conditions, it may be possible to reduce the water content of the soil to near zero. However, it should also be noted from the moisture-density curves for this soil (Figure 4) that the ultimate density attainable with such a dry soil will be quite low. Conversely, higher density would be achieved at higher water content, at least until the optimum is reached. Also, because of the fineness of the material, compaction under conditions of a prevailing wind could make the task impractical if not impossible. The river-sand material (item 3) was actually classified as a sandy silt material and had a high fines content with approximately 55 percent passing the No. 200 sieve. Moisture-density characteristics of this material were characteristic of a fine-grained soil (Figure 5). Difficulty was also experienced in field drying this material, and the final water content prior to compaction was about 6 to 7 percent. Soils of this type could also possibly be reduced to near-zero water content under arid climatic conditions; however, the final compacted density would be quite low. In this investigation, the densities achieved with both compactors were acceptable, i.e. about 95 and 90 percent, respectively, with the vibratory and impact rollers. The soil profile for the impact roller (Figure 16) indicated lower densities at the surface and 48-in. depth which could be a result of drum slippage at the surface and failure to impart sufficient impact energy at the lower depths. In fact, there appeared to be little change in density in the first lift after compaction in the second lift. Although the density profiles indicate a slight decrease in density in the first lift, the difference is thought to be a result of sampling variation.

62. Generally, acceptable density values were obtained in the limestone (item 1), gravelly sand (item 4), and sand tailings (item 5) even though none of these materials were reduced to zero water content. When the final

densities were recomputed as percentages of the actual CE-55 density at the field water content, test results appeared even more favorable and reflected more realistically.

63. From these observations, it would appear that, under certain conditions, a practical alternative might be to compact a soil at some water content above zero but below the conventional optimum value with full knowledge of the results to be expected. Conditions that would warrant such an approach include expediency of the situation, inability to adjust the water content of the in situ soil, or a calculated decision to compact the soil at or above the in situ value in order to obtain the highest density value attainable. An approach of this type could be particularly acceptable under expedient military operations; however, the designer should be thoroughly familiar with the moisture-density relations of the soil involved and be fully cognizant of the projected engineering behavior of the compacted material (including effects of subsequent wetting or settlement if this can occur as a result of dust control, watering, irrigation, or leaking from damaged water pipes).

64. The debris material which was placed in item 1 of lane 2 in a single 3.5-ft-thick lift consisted mostly of silt, with remains of base course aggregate and large pieces of concrete fragments. Density profiles for this material indicated decreasing density with depth. The large difference between the density value at the upper surface and at 48 in. (Figure 21) suggests that some difficulty might be encountered in attempting to compact such material in a bomb crater cavity.

65. In item 1 of lane 1, cause for the lower densities near the upper regions is unclear. Perhaps the equipment employed was not suitable for the application.

66. Generally, the initial densities prior to compaction were higher in lane 1 than in lane 2 which would indicate precompaction by the crawler tractor during spreading operations on each lift. Overall increase in density was generally larger in lane 2 than in lane 1 (Figure 22); however, the net increase in compaction energy level was longer in lane 1 in three of five of the soils involved (Figure 24).

67. The high theoretical rate of production of the impact roller also serves to make this type of compaction concept attractive; however, the diverse results obtained with the different soil types suggest a need for

further evaluation of the equipment to better define the limitations and capabilities of the impact roller.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

68. Based on the results of this investigation, the following conclusions are drawn:

- a. Compaction of soils at the near-zero water content state is a practical concept but is primarily applicable for nonplastic soils with a low fines contents.
- b. Soils having high fines content (such as the silty clay and river-sand materials evaluated in this study) are extremely difficult to dry, and attempts to achieve significant reduction in water content may be impractical when large qualities of soil are involved.
- c. For soils having high fines content, an alternate approach to dry or optimum moisture-content compaction is compaction at an intermediate water content, either the in situ water content or a higher value.
- d. The advantages to c above are attainment of a higher soil density than could be obtained at near-zero water content and less expenditure of construction effort. The disadvantage is that the soil density would be lower than that obtained at optimum water content.
- e. Both compactors used in this study generally gave comparable and acceptable results and could be used satisfactorily for dry-soil compaction.
- f. Precompaction of the thinner lifts in lane 1 by the crawler tractor during spreading operations precluded full utilization of the compaction potential of the vibratory compactor.
- g. Rotational slippage of the drum on the impact roller could have affected density values in the upper zone.
- h. Results with the impact roller with respect to deep compaction were inconsistent and could have been caused by surface slippage, failure to impart sufficient impact energy to the deeper zones, or a combination of both.
- i. The theoretical production rate of the impact roller makes it highly attractive from an efficiency standpoint and on this basis strongly warrants further evaluation.

Recommendations

69. As a result of the findings of this investigation, the following recommendations are presented:

a. Undertake a study to develop broad guidance for expedient compaction of soils at the dry and nonoptimum water content conditions.

b. Address such items as the candidate soils for dry compaction and alternate nonzero-water content compaction, the approach for selecting water content, the means of compaction, and the probable results and expected behavior of the compacted soil.

c. Undertake a comprehensive field study to evaluate in depth the capabilities and limitations of the impact-type roller employed in this investigation with a view toward defining optimum application and employment of the equipment, particularly in expedient military construction.

REFERENCES

Clifford, J. M. 1982. "The Development and Use of Impact Rollers in the Construction of Earthwork in Southern Africa," Council for Scientific and Industrial Research, C5IR Research Report No. 373, Bulletin 16, Pretoria, South Africa.

Department of Defense. "Test Method for Pavement Subgrade, Subbase, and Base-Course Material" in preparation, (MIL-STD-621), Washington, DC.

Forssblad, Lars. 1981. "Vibratory Soil and Rock Fill Compaction," Dynapac Maskin AB, Salem, Sweden.

Kleyn, E. G., Maree, J. H., and Savage, P. F. 1982. "The Application of a Portable Pavement Dynamics Cone Penetrometer to Determine In-Situ Bearing Properties of Load Pavement Layers and Subgrades in South Africa," Proceedings of the Second European Symposium of Penetration Testing, Amsterdam.

Lee, Peter Y., and Suedkamp, Richard J. 1972. "Characteristics of Irregularly Shaped Compaction Curves," Highway Research Record Number 381, Compaction and Stabilization, Highway Research Board, National Research Council, Washington, DC.

Ridgen, P. J., and Clifford, J. M. 1981. "Impact Rolling--A New Earthworks Technology," Proceedings of the Third Conference on Road Engineering Association of Asia and Australia, Taipei, Taiwan.

Table 1

Surface Elevation Data, Lane 1

Item	Station No.	Elevation, in., Lift 1 Before Compaction	Elevation, in., Lift 1 After Compaction	Elevation, in., Lift 2 Before Compaction	Elevation, in., Lift 2 After Compaction	Elevation, in., Lift 3 Before Compaction	Elevation, in., Lift 3 After Compaction	Elevation, in., Lift 4 Before Compaction	Elevation, in., Lift 4 After Compaction
1	0	11.8	10.8	17.2	16.9	25.1	24.6	30.8	30.0
	2	10.8	9.5	17.4	17.0	24.6	24.3	30.9	29.8
	4	10.2	9.3	17.6	17.1	24.6	24.2	30.3	29.9
	6	10.5	9.3	16.5	16.0	24.5	23.8	30.5	30.0
	8	9.2	8.0	15.6	15.3	24.3	23.8	29.9	30.0
	10	9.1	8.4	15.0	14.6	24.5	23.5	30.2	30.0
	12	9.5	8.5	14.9	14.5	24.2	23.4	30.7	30.1
	14	8.5	7.5	14.7	14.1	23.6	23.2	30.3	29.6
	16	7.2	6.4	14.8	14.1	23.9	23.1	30.0	29.2
	18	6.3	5.6	14.9	14.0	23.2	22.8	30.1	29.9
	20	7.3	6.4	15.3	14.8	23.3	22.8	30.0	29.6
	22	7.8	6.9	15.3	14.7	23.3	22.5	29.8	29.3
	24	7.5	7.4	14.8	13.8	23.9	22.0	29.7	28.8
2	26	7.3	7.5	14.0	13.8	22.8	22.5	29.1	29.2
	28	8.3	8.5	14.3	14.1	23.3	23.0	30.0	30.3
	30	9.5	8.7	14.2	14.2	22.5	22.3	30.1	30.0
	32	9.4	8.7	14.7	14.2	22.4	22.1	30.2	30.0
	34	9.3	8.8	14.3	14.1	22.7	22.4	30.0	30.0
	36	9.3	8.4	14.3	14.0	22.1	22.1	29.6	29.3
	38	8.7	7.8	14.7	14.3	21.7	21.2	29.2	29.0
	40	8.0	7.5	14.7	14.1	21.1	21.2	29.2	29.0
	42	7.7	7.5	13.5	13.2	21.4	21.1	28.3	28.4
	44	7.3	6.6	14.0	13.5	21.3	20.9	28.6	28.5
	46	7.7	7.4	13.9	13.5	21.1	21.0	28.1	27.1
	48	8.0	7.9	13.3	13.0	21.0	20.8	27.5	27.1
3	50	8.4	7.3	14.4	13.7	21.5	20.8	28.3	28.4
	52	7.7	7.0	14.7	13.9	21.8	21.1	29.0	28.4
	54	7.6	7.0	15.0	14.1	21.8	21.1	28.1	28.0
	56	8.2	7.4	15.7	14.9	21.9	21.1	28.6	27.8
	58	8.8	7.8	16.1	15.1	21.5	20.9	28.3	27.9
	60	8.8	7.9	15.8	14.9	21.3	21.0	28.2	28.4
	62	8.9	7.1	15.1	14.4	21.5	20.8	29.4	29.1
	64	7.5	7.2	15.2	14.2	21.5	20.8	29.4	28.5
	66	7.8	7.3	15.3	14.4	21.5	21.1	28.9	28.2
	68	7.8	7.0	15.5	14.9	21.6	21.4	28.6	27.8
	70	7.2	6.6	15.5	14.9	22.0	21.5	28.9	28.2
	72	6.7	6.1	15.0	14.4	23.0	22.5	28.8	28.2
	74	7.7	8.4	15.6	15.5	23.5	22.6	29.7	29.0
4	76	7.5	8.3	16.5	15.1	23.3	23.0	30.7	29.9
	78	7.6	7.1	16.5	15.2	24.2	23.1	30.7	30.2
	80	7.6	6.4	16.5	15.5	23.6	23.1	31.1	30.5
	82	6.9	6.0	16.1	15.4	24.2	23.1	31.4	30.5
	84	7.1	6.1	16.3	15.4	24.1	23.0	31.4	30.3
	86	7.1	6.3	16.3	15.4	23.7	22.9	31.5	30.1
	88	8.3	6.9	16.4	15.3	24.3	23.0	31.7	30.0
	90	8.4	7.3	16.2	15.7	23.8	22.7	31.7	29.8
	92	8.2	7.8	17.1	15.8	23.6	22.4	31.9	30.1
	94	8.4	8.4	17.4	16.0	23.8	22.5	31.1	30.5
	96	8.7	9.0	17.0	16.0	24.3	22.8	31.6	30.2
	98	8.5	9.5	17.2	16.1	24.0	22.4	31.2	30.1
5	100	8.9	9.2	16.4	15.8	23.1	22.3	31.0	30.0
	102	8.7	8.7	16.0	15.3	23.5	22.6	30.8	30.3
	104	8.6	8.5	15.9	15.0	24.1	23.4	31.0	30.5
	106	8.1	8.4	16.5	15.2	24.5	23.8	31.3	30.7
	108	8.1	8.4	16.7	15.8	24.8	23.9	31.7	30.8
	110	8.8	8.6	17.2	16.2	24.6	23.7	31.8	31.4
	112	9.0	8.1	17.2	16.2	23.9	23.3	32.3	31.7
	114	9.1	7.6	17.6	16.5	23.7	22.8	32.9	31.9
	116	9.1	7.5	17.9	17.1	24.0	23.0	32.9	32.1
	118	9.1	7.9	18.6	17.6	24.2	23.6	33.1	32.0
	120	9.4	8.5	18.6	18.0	24.9	24.0	33.3	32.2
	122	9.4	9.6	18.9	18.5	25.5	24.6	33.3	32.0
	124	10.9	10.9	19.6	18.6	25.9	25.4	33.0	31.9

(Continued)

Table 1 (Concluded)

Item	Station No.	Elevation, in., Lift 5		Elevation, in., Lift 6		Elevation, in., Lift 7		Elevation, in., Lift 8	
		Before Compaction	After Compaction	Before Compaction	After Compaction	Before Compaction	After Compaction	Before Compaction	After Compaction
1	0	35.4	34.9	44.1	43.4	51.2	50.1	57.8	56.1
	2	35.1	35.1	43.5	42.6	51.5	48.9	57.2	55.4
	4	34.8	35.0	43.9	42.7	51.1	49.6	55.8	55.9
	6	35.3	35.4	43.3	42.7	50.7	49.4	56.4	55.4
	8	36.3	36.3	43.5	43.1	50.6	50.0	56.2	54.9
	10	36.8	37.0	43.7	42.7	50.8	49.7	55.9	54.8
	12	37.3	36.7	43.2	42.8	50.3	49.3	56.0	55.1
	14	37.6	37.6	43.4	42.4	49.8	49.1	56.3	55.5
	16	37.5	37.1	43.0	42.5	50.0	49.4	56.2	55.4
	18	37.5	37.0	42.5	42.0	50.0	49.5	56.1	55.8
	20	38.3	37.7	42.0	41.7	49.9	49.4	57.1	56.1
	22	37.5	36.5	41.7	41.9	50.5	49.5	57.3	56.0
	24	37.5	37.0	42.0	41.3	49.7	48.4	57.0	56.3
2	26	37.6	37.3	41.6	41.6	48.0	48.1	56.2	55.7
	28	36.8	36.5	42.7	42.1	49.1	49.3	55.8	56.4
	30	36.1	36.1	43.8	43.0	49.1	49.9	56.7	56.6
	32	36.5	36.5	44.0	44.2	50.4	50.2	57.6	57.0
	34	37.2	36.6	44.1	44.0	50.7	50.5	57.8	57.4
	36	37.9	37.3	43.1	42.9	51.3	50.5	57.6	57.5
	38	38.8	38.5	43.4	43.1	51.1	51.0	57.8	57.7
	40	38.8	38.0	43.5	43.2	51.9	51.1	58.1	57.4
	42	38.5	38.2	43.5	43.0	51.4	51.0	57.9	57.7
	44	38.5	38.4	43.3	42.9	51.8	51.3	58.1	57.4
	46	38.5	38.3	43.5	43.4	52.1	51.3	57.6	57.0
	48	37.9	38.6	43.6	43.4	52.2	51.3	57.5	56.5
3	50	37.8	37.5	44.0	43.5	51.7	51.0	57.0	56.5
	52	37.4	37.3	43.3	43.4	51.3	50.7	55.6	54.8
	54	37.5	37.3	43.9	43.7	51.1	51.0	54.2	54.7
	56	37.7	36.4	44.2	43.9	51.3	50.8	54.8	54.7
	58	36.3	36.0	43.7	43.3	50.9	50.2	54.8	55.0
	60	36.3	36.0	43.6	43.5	50.3	49.7	55.4	55.3
	62	36.2	35.7	43.6	43.3	50.0	49.3	56.1	55.9
	64	36.0	35.5	44.2	43.5	49.4	48.5	56.0	55.0
	66	36.2	36.2	44.8	44.2	48.9	48.1	55.5	55.1
	68	36.6	36.4	44.7	44.5	48.3	48.3	55.8	55.7
	70	36.7	36.5	44.5	43.9	48.7	49.0	56.5	56.3
	72	37.3	37.0	44.8	44.1	48.8	48.6	57.1	56.5
	74	37.9	37.0	44.7	44.2	48.1	48.1	57.2	56.3
4	76	38.4	37.6	43.8	44.1	49.7	49.0	56.4	55.5
	78	38.1	37.5	43.6	43.8	47.9	48.4	55.5	55.7
	80	39.1	37.4	43.6	43.7	48.9	48.3	55.3	55.8
	82	38.6	37.2	45.5	44.3	49.2	49.0	55.6	56.5
	84	37.5	37.1	46.5	45.2	50.9	49.6	57.8	57.4
	86	38.3	37.3	45.4	46.0	51.1	50.5	58.9	57.8
	88	38.6	37.3	46.7	45.8	51.2	50.4	58.5	58.3
	90	38.2	37.4	47.5	45.4	51.5	50.5	58.8	58.2
	92	38.1	37.5	46.8	45.1	51.6	50.6	59.2	57.4
	94	39.0	38.3	47.9	45.1	51.4	51.2	59.4	56.2
	96	40.4	39.2	47.0	45.5	52.0	51.6	58.3	56.8
	98	41.0	39.7	46.7	45.5	53.3	51.9	59.0	57.5
5	100	40.0	39.6	49.6	45.8	53.4	52.3	58.1	58.6
	102	40.5	39.6	46.3	46.2	52.5	52.3	58.4	58.7
	104	40.9	39.9	46.3	46.0	51.8	51.7	58.1	58.0
	106	40.9	39.8	46.2	46.1	51.6	51.1	55.5	57.8
	108	39.9	39.4	46.9	46.3	51.7	51.1	59.2	58.1
	110	39.8	38.8	47.6	42.2	51.7	51.1	59.1	58.1
	112	39.2	38.7	47.8	46.6	51.5	50.7	58.7	58.1
	114	38.9	38.5	47.7	46.4	50.9	50.4	58.1	57.9
	116	39.2	38.7	47.5	46.3	50.6	50.8	57.9	57.2
	118	39.6	38.9	47.3	46.1	51.0	51.0	59.9	57.9
	120	40.9	39.0	46.3	46.2	51.3	51.0	60.[illegible]	58.0
	122	40.3	38.7	45.4	46.3	51.7	50.9	59.[illegible]	57.7
	124	39.2	38.5	44.9	45.7	50.8	49.9	59.6	58.1

Table 2

Mean Surface Elevation Data, Lane 1

Item	Elevation, in., Lift 1					Elevation, in., Lift 2				
	Before Compaction		After Compaction			Before Compaction		After Compaction		
	Mean	Standard Deviation	Mean	Standard Deviation	Mean Difference	Mean	Standard Deviation	Mean	Standard Deviation	Mean Difference
1	8.9	1.6	8.0	1.5	0.9	15.7	1.1	15.1	1.2	0.6
2	8.3	0.8	7.9	0.7	0.4	14.2	0.5	13.8	0.4	0.4
3	7.9	0.7	7.2	0.6	0.7	15.3	0.5	14.6	0.5	0.7
4	7.9	0.6	7.4	1.2	0.5	16.6	0.4	15.6	0.3	1.0
5	9.0	0.8	8.6	0.9	0.4	17.5	1.2	16.6	1.3	0.9
	Elevation, in., Lift 3					Elevation, in., Lift 4				
1	24.0	0.7	23.4	0.8	0.6	30.2	0.4	29.7	0.4	0.5
2	22.0	0.8	21.7	0.8	0.3	29.1	0.9	29.0	1.1	0.1
3	21.9	0.6	21.3	0.6	0.6	28.8	0.5	28.3	0.5	0.5
4	23.9	0.3	22.8	0.3	1.1	31.3	0.4	30.2	0.2	1.1
5	24.4	0.8	23.6	0.8	0.8	32.2	1.0	31.4	0.8	0.8
	Elevation, in., Lift 5					Elevation, in., Lift 6				
1	36.7	1.2	36.4	1.0	0.3	43.0	0.8	42.5	0.6	0.5
2	37.6	0.9	37.5	0.9	0.1	43.3	0.7	43.1	0.7	0.2
3	36.9	0.7	36.5	0.7	0.4	44.2	0.5	43.8	0.4	0.4
4	38.8	1.0	37.8	0.8	1.0	46.0	1.5	45.0	0.8	1.0
5	39.9	0.7	39.1	0.5	0.8	46.9	1.2	45.9	1.1	1.0
	Elevation, in., Lift 7					Elevation, in., Lift 8				
1	50.5	0.6	49.4	0.4	1.1	56.6	0.6	55.6	0.5	1.0
2	50.8	1.4	50.5	1.0	0.3	57.4	0.8	57.0	0.6	0.4
3	49.9	1.3	49.3	1.1	0.6	55.8	0.9	55.5	0.7	0.3
4	50.8	1.5	50.0	1.2	0.8	57.8	1.6	56.9	1.0	0.9
5	51.6	0.7	51.1	0.7	0.5	58.7	1.3	58.0	0.3	0.7

Table 3

Summary of Mean Soil Elevation Difference,* Lane 1

Lift	Mean Elevation Difference for Item Indicated, in.				
	1	2	3	4	5
1	0.9	0.4	0.7	0.5	0.4
2	0.6	0.4	0.7	1.0	0.9
3	0.6	0.3	0.6	1.1	0.8
4	0.5	0.1	0.5	1.1	0.8
5	0.3	0.1	0.4	1.0	0.8
6	0.5	0.2	0.4	1.0	1.0
7	1.1	0.3	0.6	0.8	0.5
8	1.0	0.4	0.3	0.9	0.5
Total	3.4/2.1**	2.2	4.2	7.4	5.7
Mean	0.6/1.1†	0.3	0.5	0.9	0.7

* Difference between mean elevation before and after compaction.

** Lifts 1-6 = debris, lifts 7 and 8 = limestone.

† Debris/limestone.

Table 4

Summary of Dry Density and Water Content Data, Lane 1

Lane	Item	Soil Type	CE-55 Maximum Density lb/cu ft	Depth in.	Before Compaction Dry Density lb/cu ft	Before Compaction Percent CE-55 Maximum Density	Before Compaction Water Content percent	After Compaction Dry Density lb/cu ft	After Compaction Percent CE-55 Maximum Density	After Compaction Water Content percent
1	1	Crushed	132.5	0	115.0	86.8	2.0	127.4	96.2	3.8
		limestone	--	12	116.0	87.6	2.0	125.7	94.9	1.4
		debris		24	115.6	--	7.3	124.3	--	8.2
				36	116.0	--	8.4	128.3	--	8.6
				48	112.8	--	10.7	131.3	--	10.3
			0-12"	Avg	115.5	87.2	2.0	126.6	95.6	2.6
			24-36"	Avg	114.8	--	8.8	128.0	--	9.0
1	2	Silty clay	115.5	0	100.2	86.8	14.4	105.8	91.6	14.5
				12	99.7	86.3	15.4	103.9	90.0	14.6
				24	100.6	87.1	14.6	102.9	89.1	14.2
				36	99.3	86.0	15.2	104.1	90.1	14.4
				48	99.1	85.5	16.1	102.9	89.1	15.3
			Avg		99.8	86.3	15.1	103.9	90.0	14.6
1	3	River sand	117.7	0	100.3	85.2	5.1	110.6	94.0	7.1
				12	100.7	85.6	5.2	110.3	93.7	6.2
				24	99.2	84.3	5.7	106.3	90.3	6.6
				36	99.6	84.6	6.9	104.4	88.7	6.3
				48	99.2	84.3	6.5	105.5	89.6	5.9
			Avg		99.8	84.8	5.9	107.4	91.3	6.4
1	4	Gravelly	120.7	0	103.4	85.7	3.7	109.8	91.0	4.3
		sand		12	103.9	86.1	3.7	118.2	97.9	4.1
				24	101.1	83.8	4.0	116.2	96.3	3.8
				36	100.8	83.5	5.0	115.4	95.5	3.6
				48	100.7	83.4	4.6	117.1	97.0	4.6
			Avg		102.0	84.5	4.2	115.3	95.5	4.1

(Continued)

Table 4 (Concluded)

				Before Compaction				After Compaction		
Lane	Item	Soil Type	CE-55 Maximum Density lb/cu ft	Depth in.	Dry Density lb/cu ft	Percent CE-55 Maximum Density	Water Content percent	Dry Density lb/cu ft	Percent CE-55 Maximum Density	Water Content percent
1	5	Sand tailings	113.0	0	100.6	89.0	2.1	105.1	93.0	2.2
				12	100.5	88.9	2.3	111.6	98.8	3.2
				24	100.9	89.3	2.0	111.8	98.9	2.5
				36	98.3	87.0	2.9	112.3	99.4	2.5
				48	98.4	87.1	2.2	110.1	97.4	2.3
			Avg		99.7	88.3	2.3	110.2	97.5	2.5

Table 5
Dynamic Penetrometer Data, Lane 1

Item	Lifts	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm
1	1-4	28	28	10	2.8
		157	129	10	12.9
		250	93	10	9.3
		330	80	10	8.0
		398	68	10	6.8
		459	61	10	6.1
		533	74	10	7.4
		594	61	10	6.1
		669	75	10	2.5
1	1-8	20	20	5	4.0
		127	107	5	21.4
		182	55	5	11.0
		223	41	5	8.2
		263	40	5	8.0
		305	42	5	8.4
		338	33	5	6.6
		368	30	5	6.0
		397	29	5	5.8
		430	33	5	6.6
		460	30	5	6.0
		498	38	5	7.6
		533	35	5	7.0
		561	28	5	5.6
		593	32	5	6.4
		627	34	5	6.8
		657	30	5	6.0
		675	18	5	3.6
		702	29	5	5.4
		728	26	5	5.2
		762	34	5	6.8
		788	26	5	5.2
		818	30	5	6.0
		840	22	5	4.4
		860	20	5	4.0
		885	25	5	5.0
		908	23	5	4.6
		933	25	5	5.0
		965	32	5	6.4
		985	20	5	4.0

(Continued)

Table 5 (Continued)

Item	Lifts	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm
2	1-4	14	14	10	1.4
		183	169	10	16.9
		298	115	10	11.5
		410	112	10	11.2
		498	88	10	8.8
		597	99	10	9.9
		679	89	10	8.9
	1-8	17	17	5	3.4
		88	71	5	14.2
		165	77	5	15.4
		207	42	5	8.4
		260	53	5	10.6
		338	78	5	15.6
		395	57	5	11.4
		448	53	5	10.6
		492	44	5	8.8
		533	41	5	8.2
		578	45	5	9.0
		632	54	5	10.8
		695	60	5	12.0
		743	48	5	9.6
		800	57	5	11.4
		852	52	5	10.4
		905	53	5	10.6
3	1-4	29	29	10	2.9
		179	150	10	15.0
		279	102	10	10.0
		382	103	10	10.3
		478	96	10	9.6
		552	74	10	7.4
		638	86	10	8.6
		771	133	10	13.3
3	1-8	28	28	5	5.6
		125	97	5	19.4
		188	63	5	12.6
		237	49	5	9.8
		278	41	5	8.2
		313	35	5	7.0
		350	37	5	7.4
		388	38	5	7.6

(Continued)

Table 5 (Continued)

Item	Lifts	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm
3	1-8	442	54	5	10.8
		488	46	5	9.2
		527	39	5	7.8
		562	35	5	7.0
		602	40	5	8.0
		642	40	5	8.0
		683	41	5	8.2
		725	42	5	8.4
		763	38	5	7.6
		800	37	5	7.4
		840	40	5	8.0
		878	38	5	7.6
		917	39	5	7.8
		953	36	5	7.2
		977	24	5	4.8
4	1-4	70	70	5	14.0
		318	248	5	49.6
		405	87	5	17.4
		473	68	5	13.6
		536	63	5	12.6
		592	56	5	11.2
		637	45	5	9.0
		765	128	5	25.6
4	1-8	68	68	5	13.6
		300	232	5	46.4
		392	92	5	18.4
		457	65	5	13.0
		512	55	5	11.0
		563	51	5	10.2
		603	40	5	8.0
		645	42	5	8.4
		678	33	5	6.6
		717	39	5	7.8
		750	33	5	6.6
		787	37	5	7.4
		817	30	5	6.0
		848	31	5	6.2
		880	32	5	6.4
		907	27	5	5.4
		937	30	5	6.0
		953	16	5	3.2

(Continued)

Table 5 (Concluded)

Item	Lifts	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm
5	1-4	65	65	5	13.0
		302	237	5	47.4
		390	88	5	17.6
		463	73	5	14.6
		519	56	5	11.2
		573	54	5	10.8
		622	49	5	9.8
		669	47	5	9.4
		680	11	5	2.2
		710	30	5	6.0
		744	34	5	6.8
		880	61	5	13.0
5	1-8	57	57	5	11.4
		320	263	5	52.6
		413	93	5	18.6
		473	60	5	12.0
		533	60	5	12.0
		582	49	5	9.8
		628	46	5	9.2
		667	39	5	7.8
		705	38	5	7.6
		745	40	5	8.0
		787	42	5	8.4
		822	35	5	7.0
		860	38	5	7.6
		893	33	5	6.6
		932	39	5	7.8
		970	38	5	7.6

Table 6

Surface Elevation Data, Lane 2

Item	Station ft	Elevation, in., First Lift Before Compaction	Elevation, in., First Lift After Compaction	Elevation, in., Second Lift Before Compaction	Elevation, in., Second Lift After Compaction
1	0	26.5	24.0	39.6	38.1
	1	0.0	25.6	0.0	38.0
	2	27.9	26.0	40.1	40.5
	3	0.0	25.5	0.0	39.9
	4	27.3	24.1	40.8	39.7
	5	0.0	24.0	0.0	39.8
	6	27.5	24.0	41.4	39.8
	7	0.0	24.3	0.0	39.7
	8	26.9	24.4	40.4	39.6
	9	0.0	22.8	0.0	39.3
	10	26.9	22.5	40.9	39.7
	11	0.0	22.7	0.0	40.3
	12	26.3	23.1	41.6	41.2
	13	0.0	23.4	0.0	40.8
	14	27.2	23.0	41.9	40.4
	15	0.0	23.6	0.0	40.1
	16	27.1	24.3	41.5	40.5
	17	0.0	24.7	0.0	40.7
	18	26.1	22.9	41.9	40.7
	19	0.0	21.7	0.0	41.5
	20	25.5	21.6	42.6	40.7
	21	0.0	21.5	0.0	42.0
	22	24.9	21.4	42.8	41.9
	23	0.0	21.1	0.0	41.9
	24	25.5	21.4	43.5	42.1
2	25	0.0	22.1	0.0	41.5
	26	26.8	23.2	45.4	41.7
	27	0.0	23.8	0.0	44.1
	28	27.2	22.8	48.0	45.5
	29	0.0	22.5	0.0	47.6
	30	26.8	23.4	51.0	48.6
	31	0.0	23.5	0.0	51.7
	32	26.2	23.1	52.5	52.1
	33	0.0	22.8	0.0	51.8
	34	26.5	23.2	53.3	50.9
	35	0.0	24.1	0.0	50.1
	36	26.9	25.1	54.0	50.9
	37	0.0	24.4	0.0	52.7
	38	26.9	23.4	54.6	52.9
	39	0.0	23.4	0.0	51.9
	40	26.5	24.0	53.5	51.5
	41	0.0	23.8	0.0	51.7
	42	26.3	23.5	52.8	51.2

(Continued)

Table 6 (Continued)

Item	Station ft	Elevation, in., First Lift Before Compaction	Elevation, in., First Lift After Compaction	Elevation, in., Second Lift Before Compaction	Elevation, in., Second Lift After Compaction
2	43	0.0	23.4	0.0	50.6
	44	26.4	24.0	52.4	50.0
	45	0.0	24.6	0.0	49.4
	46	26.5	24.2	52.2	50.5
	47	0.0	23.1	0.0	50.2
	48	26.5	23.7	52.6	50.9
	49	0.0	24.6	0.0	50.8
3	50	26.8	24.3	52.6	50.8
	51	0.0	22.7	0.0	51.1
	52	27.1	22.9	53.3	51.1
	53	0.0	24.0	0.0	51.9
	54	27.1	25.7	53.8	52.1
	55	0.0	25.6	0.0	53.5
	56	27.9	23.4	54.2	52.2
	57	0.0	23.5	0.0	52.8
	58	27.9	25.2	53.8	52.2
	59	0.0	27.1	0.0	52.4
	60	27.8	24.8	53.5	52.3
	61	0.0	23.7	0.0	50.2
	62	28.2	23.8	53.2	49.4
	63	0.0	25.8	0.0	49.9
	64	28.2	27.1	52.3	50.8
	65	0.0	23.5	0.0	50.9
	66	27.6	23.1	51.8	49.8
	67	0.0	24.4	0.0	49.9
	68	27.5	26.9	52.2	50.8
	69	0.0	20.2	0.0	54.4
	70	27.4	24.7	51.8	53.5
	71	0.0	24.7	0.0	51.8
	72	26.1	26.2	51.5	50.5
	73	0.0	26.9	0.0	50.1
	74	24.5	27.0	51.9	50.1
4	75	0.0	26.4	0.0	54.8
	76	24.2	24.4	52.4	54.6
	77	0.0	18.9	0.0	53.1
	78	24.5	18.8	52.8	50.1
	79	0.0	21.8	0.0	46.8
	80	24.9	24.3	53.2	47.6
	81	0.0	25.8	0.0	52.2
	82	24.9	26.1	53.3	52.9
	83	0.0	26.1	0.0	50.5
	84	24.9	21.6	53.8	49.7
	85	0.0	19.7	0.0	48.3

(Continued)

(Sheet 2 of 3)

Table 6 (Concluded)

Item	Station ft	Elevation, in., First Lift Before Compaction	After Compaction	Elevation, in., Second Lift Before Compaction	After Compaction
4	86	25.3	20.7	54.1	48.2
	87	0.0	22.7	0.0	53.0
	88	25.5	24.5	53.6	53.5
	89	0.0	25.5	0.0	53.2
	90	25.3	26.4	53.5	52.5
	91	0.0	26.2	0.0	49.3
	92	25.1	24.4	53.5	47.3
	93	0.0	20.4	0.0	51.8
	94	25.2	20.9	53.9	53.7
	95	0.0	23.4	0.0	53.4
	96	25.4	24.7	53.8	52.7
	97	0.0	26.7	0.0	51.3
	98	25.0	27.1	54.5	48.3
	99	0.0	26.4	0.0	48.7
5	100	24.5	21.8	55.1	54.0
	101	0.0	23.5	0.0	54.9
	102	24.0	25.2	55.0	54.2
	103	0.0	26.3	0.0	53.2
	104	24.0	27.3	54.6	51.5
	105	0.0	27.9	0.0	48.7
	106	25.2	25.0	55.4	49.5
	107	0.0	22.1	0.0	54.4
	108	25.1	23.9	55.8	55.5
	109	0.0	25.4	0.0	54.3
	110	25.4	26.7	55.9	53.0
	111	0.0	26.8	0.0	50.5
	112	25.2	24.8	55.3	47.0
	113	0.0	20.1	0.0	49.7
	114	25.4	22.2	54.8	54.3
	115	0.0	23.7	0.0	54.7
	116	25.0	25.5	54.0	53.5
	117	0.0	26.2	0.0	52.0
	118	25.1	24.9	53.5	49.5
	119	0.0	20.8	0.0	47.2
	120	27.1	22.7	53.2	49.3
	121	0.0	24.9	0.0	53.6
	122	27.7	26.7	53.2	54.4
	123	0.0	28.3	0.0	53.1
	124	28.3	28.4	53.2	52.5
	125	0.0	26.8	0.0	50.5

(Sheet 3 of 3)

Table 7

Mean Surface Elevation Data, Lane 2

Item	Elevation, in., Lift 1					Elevation, in., Lift 2				
	Before Compaction		After Compaction			Before Compaction		After Compaction		
	Mean	Standard Deviation	Mean	Standard Deviation	Mean Difference	Mean	Standard Deviation	Mean	Standard Deviation	Mean Difference
1	26.6	0.9	23.3	1.4	3.3	41.5	1.1	40.4	1.1	1.1
2	26.6	0.3	23.6	0.7	3.0	51.9	2.6	49.6	3.2	2.3
3	27.2	1.0	25.0	1.6	2.2	52.8	0.9	51.4	1.3	1.4
4	25.0	0.4	23.8	2.7	1.2	53.5	0.6	51.1	2.5	2.4
5	25.5	1.3	24.9	2.3	0.6	54.5	1.0	52.2	2.4	2.3

Table 8

Summary of Dry Density and Water Content Data, Lane 2

Lane	Item	Soil Type	CE-55 Maximum Density lb/cu ft	Lift No.	Before Compaction: Depth in.	Before Compaction: Dry Density lb/cu ft	Before Compaction: Percent CE-55 Maximum Density	Before Compaction: Water Content percent	After Compaction: Depth in.	After Compaction: Dry Density lb/cu ft	After Compaction: Percent CE-55 Maximum Density	After Compaction: Water Content percent	Compaction Applied
2	1	Debris	--	1	0	115.1	--	9.5	0	124.7	--	8.5	6 passes
					12	113.6	--	10.1	12	121.4	--	9.8	
					24	108.9	--	9.8	24	119.0	--	11.3	
					36	103.5	--	9.7		121.7		9.9	
					Avg	110.3		9.8					
2	1	Crushed limestone	132.5	2	0	109.9	82.9	2.0	0	132.1	99.7	1.2	6 passes
		debris	--		12	112.6	85.0	2.0	12	131.9	99.6	1.2	6 passes, 2nd lift plus
										132.0	99.7	1.2	6 passes, 1st lift
					Avg	111.3	84.0	2.0	24	126.8	--	9.3	
									36	122.6	--	10.3	
									48	118.3	--	11.0	
					Avg					122.6		10.2	
2	2	Silty clay	115.5	1	0	95.9	83.0	15.6	0	103.4	89.5	13.4	6 passes
					12	94.3	81.7	17.7	12	100.0	86.6	15.6	
					24	94.0	81.4	16.0	24	96.1	83.2	17.7	
					Avg	94.7	82.0	16.4		99.8	86.4	15.6	
				2	0	97.5	84.4	17.6	0	104.9	90.8	12.5	6 passes
					12	96.9	83.9	14.7	12	102.5	88.8	13.7	
					24	96.9	83.9	13.4	24	101.8	88.1	13.6	
					--	--	--	--	36	103.2	89.4	15.1	6 passes, 2nd lift plus 6 passes, 1st lift
					--	--	--	--	48	99.6	86.2	16.0	
					Avg	97.1	84.1	15.2		102.4	88.7	14.2	
2	3	River sand	117.7	1	0	93.9	78.5	6.9	0	102.1	86.8	6.8	6 passes
					12	90.8	77.3	7.7	12	99.3	84.4	6.9	
					24	91.1	77.4	7.7	24	97.0	82.4	7.7	
					Avg	91.9	78.1	7.4		99.5	84.5	7.1	
2	3	River sand	117.7	2	0	93.4	79.4	6.0	0	103.8	88.2	6.2	6 passes, 2nd lift plus 6 passes, 1st lift
					12	92.9	78.9	6.4	12	105.2	89.4	6.9	
					24	92.9	78.9	6.8	24	107.0	90.9	6.9	
					--	--	--	--	36	100.2	85.1	8.3	
					--	--	--	--	48	96.8	82.2	8.8	
					Avg	93.1	79.1	6.4		102.6	87.2	7.4	
2	4	Gravelly sand	120.7	1	0	99.3	81.0	5.1	0	107.6	89.2	5.0	6 passes
					12	96.2	79.9	5.4	12	111.4	92.3	5.1	
					24	96.5	80.0	5.3	24	112.5	93.2	5.4	
					Avg	97.3	80.7	5.3		110.5	91.6	5.2	
				2	0	97.5	80.8	4.6	0	109.0	90.3	5.1	
					12	97.5	80.8	4.4	12	115.8	95.9	5.2	
					24	94.1	78.0	5.0	24	113.0	93.6	5.6	
					--	--	--	--	36	114.0	94.4	6.8	
					--	--	--	--	48	113.0	93.6	6.3	
					Avg	97.3	79.9	4.7		113.0	93.6	5.8	
2	5	Sand tailings	113.0	1	0	93.0	82.3	3.3	0	99.1	88.0	3.2	6 passes
					12	93.0	82.5	3.2	12	105.1	93.0	3.3	
					24	93.4	82.7	3.3	24	102.3	90.5	3.2	
					Avg	93.1	82.4	3.3		102.2	90.5	3.2	
				2	0	94.1	83.3	2.3	0	100.8	89.2	2.9	6 passes, 2nd lift plus 6 passes, 1st lift
					12	94.3	83.5	2.8	12	106.1	93.9	2.9	
					24	93.9	83.1	3.2	24	108.0	95.6	2.7	
					--	--	--	--	36	107.3	95.0	3.4	
					--	--	--	--	48	99.1	87.0	4.2	
					Avg	93.1	83.3	2.8		104.3	92.3	3.2	

Table 9

Dynamic Penetrometer Data, Lane 2

		Before Compaction			After Compaction	Before Compaction			After Compaction
Item	Lift	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm
1	1	17	0			17			
		111	94	10	9.4	107	90	5	18.0
		190	79	10	7.9	167	60	5	12.0
		275	85	10	8.5	223	56	5	11.2
		395	120	10	12.0	273	50	5	10.0
		538	143	10	14.3	335	62	5	12.4
		737	199	10	19.9	378	43	5	8.6
		893	156	10	15.6	447	69	5	13.8
		958	65	10	6.5	528	81	5	16.2
						617	89	5	17.8
						665	48	5	9.6
						737	72	5	14.4
						797	60	5	12.0
						825	28	5	5.6
						913	88	5	17.6
						940	27	5	5.4
						960	20	5	4.0
1	2	27	0			30			
		158	131	5	26.2	87	57	5	31.4
		243	85	5	17.0	257	70	5	14.0
		305	72	5	14.4	327	70	5	14.0
		365	50	5	10.0	400	73	5	14.6
		432	67	5	13.4	460	60	5	12.0
		467	35	5	7.0	497	37	5	7.4
		512	45	5	9.0	530	33	5	6.6

(Continued)

Table 9 (Continued)

		Before Compaction			After Compaction	Before Compaction			After Compaction
Item	Lift	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm
1	2	545	33	5	6.6	553	23	5	4.6
		573	28	5	5.6	580	27	5	5.4
		605	32	5	6.4	610	30	5	6.0
		637	32	5	6.4	637	27	5	5.4
		693	36	5	7.2	660	23	5	4.6
		708	35	5	7.0	683	23	5	4.6
		753	45	5	9.0	713	30	5	6.0
		792	39	5	7.8	747	34	5	6.8
		828	36	5	7.2	773	26	5	5.2
		882	53	5	10.6	817	44	5	8.8
						850	33	5	6.6
						897	47	5	9.4
2	1	27	0			22			
		239	212	10	21.2	138	116	5	23.2
		581	342	10	34.2	228	90	5	18.0
		755	174	10	17.4	318	90	5	18.0
						412	94	5	18.8
						518	106	5	21.2
						602	84	5	16.8
						655	53	5	10.6
						688	33	5	6.6
						718	30	5	6.0
2	2	8	0			10			
		147	139	5	27.8	117	107	5	21.4
		333	186	5	37.2	200	83	5	16.6

(Continued)

Table 9 (Continued)

		Before Compaction			After Compaction	Before Compaction			After Compaction
Item	Lift	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm
2	2	550	217	5	43.4	280	80	5	16.0
		765	215	5	43.0	357	77	5	15.4
						443	86	5	17.2
						536	93	5	18.6
						627	91	5	18.2
						697	70	5	14.0
						737	40	5	8.0
						787	50	5	10.0
						830	43	5	8.6
						880	50	5	10.0
						930	50	5	10.0
						980	50	5	10.0
3	1	30	0			37	0		
		136	106	5	21.1	165	128	5	25.6
		256	120	5	24.0	250	85	5	17.0
		471	215	5	43.0	342	92	5	18.4
		687	216	5	43.2	440	98	5	19.6
						552	112	5	22.4
						668	116	5	23.2
3	2	10	0			20	0		
		117	107	5	21.4	167	147	5	29.4
		217	100	5	20.0	267	100	5	20.0
		347	130	5	26.0	350	83	5	16.6
		572	225	5	45.0	440	90	5	18.0

(Continued)

Table 9 (Continued)

		Before Compaction			After Compaction	Before Compaction			After Compaction
Item	Lift	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm	Penetration Depth mm	Increment mm	Blows/ Increment	Penetration/ Blow mm
3	2	745	173	5	34.6	533	93	5	18.6
		805	60	5	12.0	627	94	5	18.8
		850	45	5	9.0	703	76	5	15.2
		895	45	5	9.0	763	60	5	12.0
		945	50	5	10.0	813	50	5	10.0
						870	57	5	11.4
4	1	75	0			73	0		
		312	237	5	47.4	228	155	5	31.0
		444	132	5	26.4	338	110	5	22.0
		577	133	5	26.6	446	108	5	21.6
		743	166	5	33.2	573	127	5	25.4
						672	99	5	19.8
						774	102	5	20.4
4	2	37	0			88	0		
		370	333	5	66.6	161	73	5	14.6
		530	160	5	32.0	226	65	5	13.0
		667	137	5	27.4	285	59	5	11.8
		805	130	5	27.6	358	73	5	14.6
		917	112	5	22.4	433	75	5	15.0
						515	82	5	16.4
						589	74	5	14.8
						658	69	5	13.8
						728	70	5	14.0
						791	63	5	12.6
						860	69	5	13.8
						931	71	5	14.2

(Continued)

Table 9 (Concluded)

Item	Lift	Before Compaction Penetration Depth mm	Before Compaction Increment mm	Before Compaction Blows/ Increment	After Compaction Penetration/ Blow mm	Before Compaction Penetration Depth mm	Before Compaction Increment mm	Before Compaction Blows/ Increment	After Compaction Penetration/ Blow mm
5	1	70	70	5	14.0	72			
		380	310	5	62.0	222	150	5	30.0
		633	253	5	50.6	344	122	5	24.4
		775	142	5	28.4	462	118	5	23.6
						564	102	5	20.4
						680	116	5	23.2
5	2	42	42	5	8.4	122			
		380	338	5	67.6	230	108	5	21.6
		640	260	5	52.0	332	102	5	20.4
		937	297	5	59.4	408	76	5	15.2
						478	70	5	14.0
						550	72	5	14.4
						624	74	5	14.8
						712	88	5	17.6
						767	55	5	11.0
						834	67	5	13.4
						924	90	5	18.0

(Sheet 5 of 5)

Table 10

Summary of Density Data (Percent CE-55 Maximum Density*)

			Density				
Lane	Item	Depth in.	Before Compaction	After Compaction	Increase	Percent Increase	Remarks
1	1	0	86.8	96.2	9.4	10.8	Crushed limestone
		12	87.6	94.9	7.3	8.3	Crushed limestone
		24	115.6	124.3	8.7	7.5	Debris**
		36	116.0	128.3	12.3	10.6	Debris**
		48	112.0	131.3	19.3	17.2	Debris**
	2	0	86.8	91.6	4.8	5.5	
		12	86.3	90.0	3.7	4.3	
		24	87.1	89.1	2.0	2.3	Silty clay
		36	86.0	90.1	4.1	4.8	
		48	85.5	89.1	3.6	4.2	
	3	0	85.2	94.0	8.8	10.3	
		12	85.6	93.7	8.1	9.5	
		24	84.3	90.3	6.0	7.1	River sand
		36	84.6	88.7	4.1	4.9	
		48	84.3	89.6	5.3	6.3	
	4	0	85.7	91.0	5.3	6.2	
		12	86.1	97.9	11.8	13.7	
		24	83.8	96.3	12.5	14.9	Gravelly sand
		36	83.5	95.5	12.0	14.4	
		48	83.4	97.0	13.6	16.3	
	5	0	89.0	93.0	4.0	4.5	
		12	88.9	98.8	9.9	11.1	

(Continued)

* Except as noted.
** Values are in pounds per cubic feet.

(Sheet 1 of 3)

Table 10 (Continued)

Lane	Item	Depth in.	Density: Before Compaction	Density: After Compaction	Increase	Percent Increase	Remarks
		24	89.3	98.9	9.6	10.8	Sand tailings
		36	87.0	99.4	12.4	14.3	
		48	87.1	97.4	10.3	11.8	
2	1	0	82.9	99.7	16.8	20.3	Cr. limestone
		12	85.0	99.6	14.6	17.2	Cr. limestone
		24	114.4	126.8	12.4	10.8	Debris pcf before = Avg 0 and 12, first lift
		36	113.3	122.6	11.3	10.0	Debris pcf before = Avg 24 and 36, first lift
		48	106.2	118.3	12.1	11.4	Debris pcf before = Avg 24 and 36, first lift
	2	0	84.8	90.8	6.4	7.6	
		12	83.9	88.8	4.9	5.8	Silty clay before = Avg 0" and 12", first lift
		24	83.9	88.8	4.2	5.0	
		36	82.4	89.4	7.0	8.5	Before = Avg 12" and 24", first lift
		48	81.6	86.2	4.6	5.6	
	3	0	79.4	88.2	8.8	11.1	
		12	78.9	89.4	10.5	13.3	River sand
		24	78.9	90.9	12.0	15.2	Before = Avg 0" and 12", first lift
		36	78.5	85.1	6.6	8.4	Before = Avg 12" and 24", first lift
		48	77.3	82.2	4.9	6.3	
	4	0	80.8	90.3	9.5	11.8	
		12	80.8	95.9	15.1	18.7	

(Continued)

(Sheet 2 of 3)

Table 10 (Concluded)

Lane	Item	Depth in.	Density Before Compaction	Density After Compaction	Increase	Percent Increase	Remarks
		24	78.0	93.6	15.6	20.0	Gravelly sand
		36	81.0	94.4	13.4	16.5	Before = Avg 0" and 12", first lift
		48	79.9	93.6	13.7	17.2	Before = Avg 12" and 24", first lift
5	0	83.3	89.2	5.9	7.1		
		12	83.5	93.9	10.4	12.5	Sand tailings
		24	83.1	95.6	12.5	15.0	Before = Avg 0" and 12", first lift
		36	82.3	95.0	12.7	15.4	Before = Avg 12" and 24", first lift
		48	82.5	87.0	4.5	5.5	Before = Avg 12" and 24", first lift

Table 11

Summary of Mean Density and Water Content Data

Lane	Item	Material	Density Percent CE-55 Maximum Before	After	Increase	Percent Increase
1	1	Crushed stone	87.2	95.6	8.4	9.6
	1	Debris	114.8	128.0	13.2	11.5
	2	Silty clay	86.3	90.0	3.7	4.3
	3	River sand	84.8	91.3	6.5	9.7
	4	Gravelly sand	84.5	95.5	11.0	13.0
	5	Sand tailings	88.3	97.5	9.2	10.4
2	1	Crushed stone	84.0	99.7	15.7	18.7
	1	Debris	110.6	122.6	12.0	10.9
	2	Silty clay	83.1	88.7	4.7	6.6
	3	River sand	78.6	87.2	8.6	10.9
	4	Gravelly sand	80.1	93.6	13.5	16.9
	5	Sand tailings	82.9	92.3	9.4	11.3

Table 12

Summary of Field and Laboratory Density Data

			Field Data				Laboratory Data CE-55 Density @ Field Water Content, pcf		Percent CE-55 Density			
			Before Compaction		After Compaction							
Lane	Item	Soil	Dry Density lb cu/ft	Water Content percent	Dry Density lb/cu ft	Water Content percent	Before Compaction	After Compaction	Before Compaction	After Compaction	Increase	Percent Increase
1	1	Crushed limestone	115.5	2.0	126.6	2.6	128.1	126.5	90.2	100.1	9.9	9.9
	2	Silty clay	99.8	15.1	103.9	14.6	115.3	115.5	86.6	90.0	3.4	3.8
	3	River sand	99.8	5.9	107.4	6.4	113.0	113.5	88.3	94.6	6.3	6.7
	4	Sandy gravel	102.0	4.2	115.3	4.1	114.5	114.5	89.1	100.7	11.6	11.5
	5	Sand tailing	99.7	2.3	110.2	2.5	106.2	106.0	93.9	104.0	10.1	9.7
2	1	Crushed limestone	111.3	2.0	132.0	1.2	128.1	129.8	86.9	101.7	14.8	14.6
	2	Silty clay	95.9	15.8	102.4	14.2	114.8	115.2	83.5	88.9	5.4	6.1
	3	River sand	92.5	6.9	102.6	7.4	114.0	114.7	81.1	89.5	8.4	9.4
	4	Sandy gravel	97.3	5.0	113.0	5.8	114.4	114.5	85.1	98.7	13.6	13.8
	5	Sand tailing	93.1	3.1	104.3	3.2	105.7	105.7	88.1	98.7	10.6	10.7

Table 13

Summary of Field and Laboratory Density and Compaction Energy Data

			Field Data				Laboratory Data								
			Before Compaction		After Compaction		Dry Density at Compaction Effort Indicated, pcf						Compaction Energy Index ft-lb/ft^3		Difference in Compaction Energy Index
							Precompaction Water Content			Postcompaction Water Content					
Lane	Item	Soil	Dry Density lb/cu ft	Water Content percent	Dry Density lb/cu ft	Water Content percent	CE-12	CE-26	CE-55	CE-12	CE-26	CE-55	Before Compaction	After Compaction	
1	1	Crushed limestone	115.5	2.0	126.6	2.6	117.5	123.5	128.1	116.0	121.0	126.5	8.5	55.0	46.5
	2	Silty clay	99.8	15.1	103.9	14.6	102.7	110.5	115.3	102.3	110.4	115.5	90.0	13.8	4.8
	3	River sand	99.8	5.9	107.4	6.4	102.7	107.9	113.0	103.2	108.5	113.5	8.0	22.0	14.0
	4	Sandy gravel	102.0	4.2	115.3	4.1	110.5	112.3	114.5	110.6	112.2	114.5	1	75	74
	5	Sand tailing	99.7	2.3	110.2	2.5	101.5	104.2	106.2	101.4	104.0	106.0	7.5	165.0	157.5
2	1	Crushed limestone	111.3	2.0	132.0	1.2	117.5	123.5	128.1	119.5	125.7	129.8	5.2	65.0	59.8
	2	Silty clay	95.9	15.8	102.4	14.2	103.5	110.8	114.8	102.0	110.0	115.2	5.5	12.6	7.1
	3	River sand	92.5	6.9	102.6	7.4	103.5	108.8	114.0	104.1	109.5	114.7	2.4	9.5	7.1
	4	Sandy gravel	97.3	5.0	113.0	5.8	110.8	112.5	114.4	111.4	113.0	114.5	1	26	25
	5	Sand tailing	93.1	3.1	104.3	3.2	100.8	103.8	105.7	100.9	103.8	105.7	1	30	29

Table 14

Data Summary-Change in Mean Elevation and Mean Density

Lane	Item	Total Mean Elevation Difference* TMD in.	TMD / 60 in.	Initial Density** percent CE-55	Mean Density** Increase MDI	MDI Divided by Initial Density percent
1	1	2.1	3.5	87.2	8.4	9.6
	2	2.2	3.7	86.3	3.7	4.3
	3	4.2	7.0	84.8	6.5	7.7
	4	7.4	12.3	84.5	11.0	13.0
	5	5.7	9.5	88.3	9.2	10.4
2	1	1.1	1.8	84.0	15.7	18.7
	2	5.2	8.7	83.2	5.5	6.6
	3	3.6	6.0	78.6	8.6	10.9
	4	3.7	6.2	80.1	13.5	16.9
	5	3.0	5.0	82.9	9.4	11.3

* Taken from Table 3.
** Taken from Table 11.

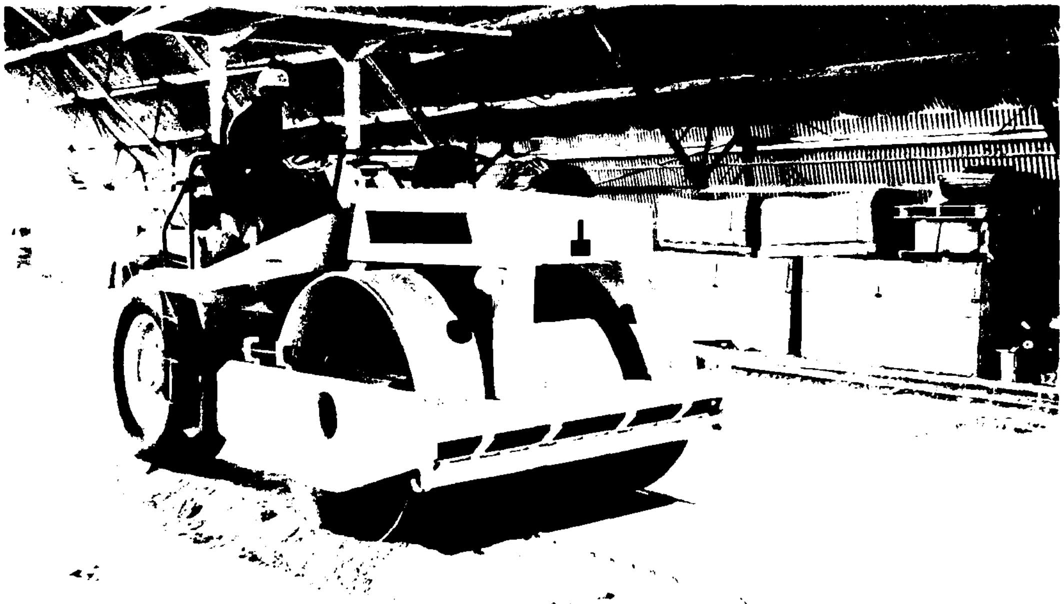


Photo 1. Vibratory compactor

Photo 2. Impact roller

APPENDIX A: DYNAMIC CONE PENETROMETER

1. The Dynamic Cone Penetrometer (DCP) has been described by Kleyn, Maree, and Savage (1982).* The DCP consists of a 16-mm-diam steel rod with a 60-deg cone at one end having a diameter of 20 mm (Figure A1). The rod is driven into the soil by means of a 8-kg sliding weight hammer having a 575-mm fall. Penetration of the DCP into the soil is determined by means of a measuring rod attached parallel to the driven rod. At the lower end, the measuring rod rests on the soil and is connected to the drive rod by a transverse member which is fixed to the measuring rod at one end and attached to the drive rod at the other end by means of a spring clip device. The spring clip holds the drive rod in place to maintain lateral spacing between rods but allows free vertical measurement of the drive rod.

2. At the upper end, the measuring rod is attached to the drive rod by a transverse member which is fixed to the drive rod at one end and is attached to the measuring rod by a spring clip which moves freely down the measuring rod as the drive rod penetrates the soil. Penetration of the drive rod is determined by movement of the upper spring clip. In practice, the DCP is normally operated by three people -- one maintaining the instrument in a vertical position by means of the handle at the upper end of the device, another operating the hammer, and a third recording the penetration reading. A fixed number of blows is applied with the hammer, i.e., 5 to 10 blows, after which the penetration reading is recorded. By this procedure, one can determine at any depth a measure of soil resistance in terms of millimeters per blow. This valuee is termed the DCP number. Measurement may be made with this device up to a depth of 1,000 mm.

* All references cited in this Appendix are included in the References at the end of the main text.

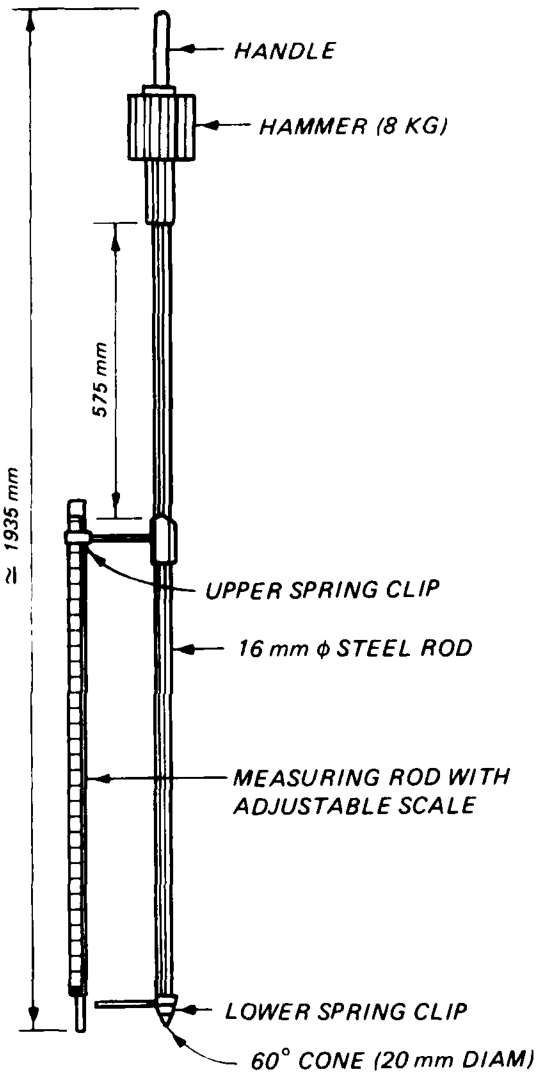


Figure A1. The portable pavement DCP

END

12-87

DTIC